Ocean Energy in Barbados

A Review of Clean Technology Options, Available Resource and Locational Guidance for Potential Areas of Interest for Commercial Development

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Energy Division/ Infrastructure and Energy Department

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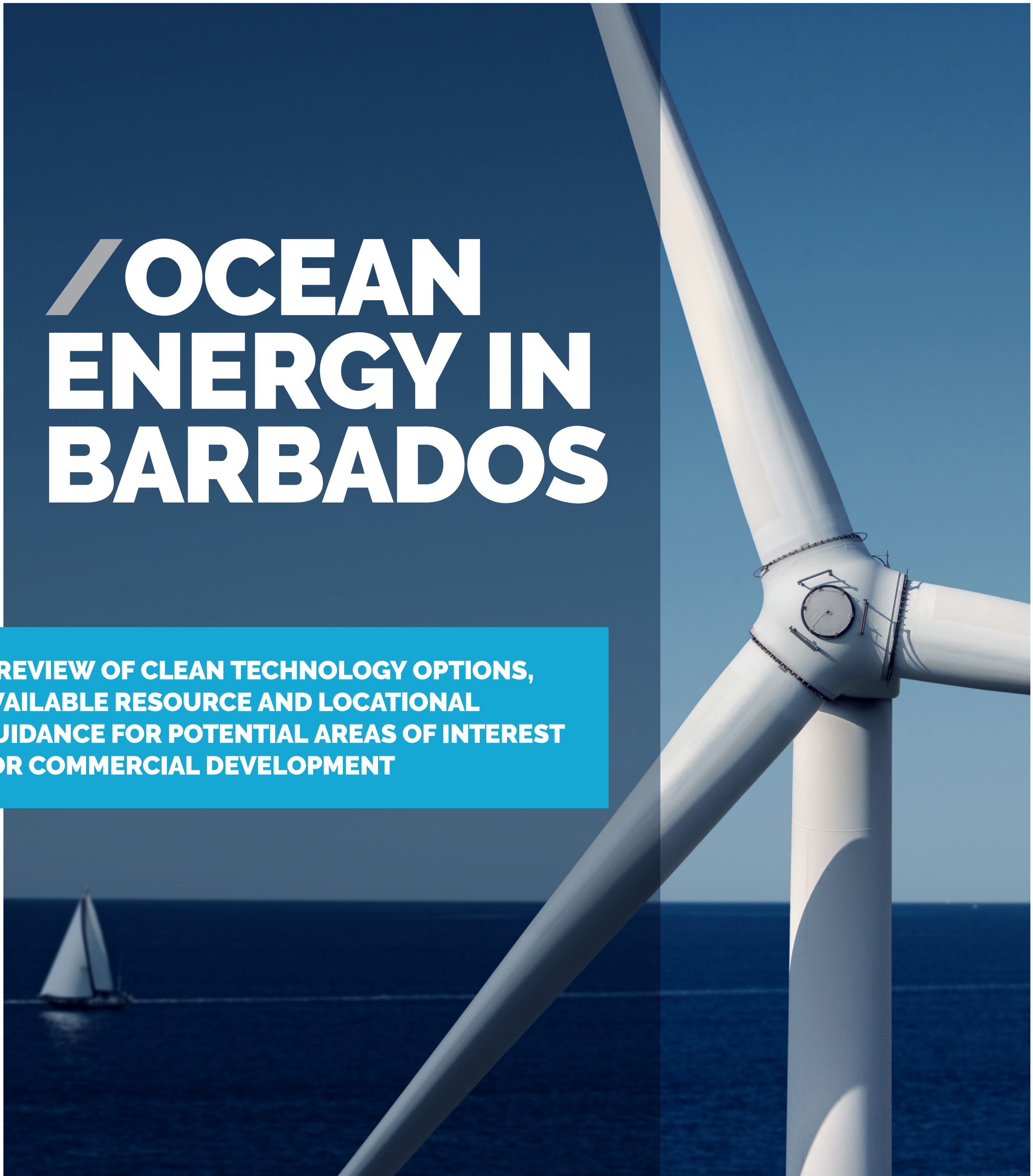
/OCEAN ENERGY IN BARBADOS



A REVIEW OF CLEAN TECHNOLOGY OPTIONS, AVAILABLE RESOURCE AND LOCATIONAL GUIDANCE FOR POTENTIAL AREAS OF INTEREST FOR COMMERCIAL DEVELOPMENT

IDB

BARBADOS MINISTRY OF Energy & Water Resources
UTILISING OUR NATURAL RESOURCES

Report to the Inter-American Development Bank

Reference : IDBR011

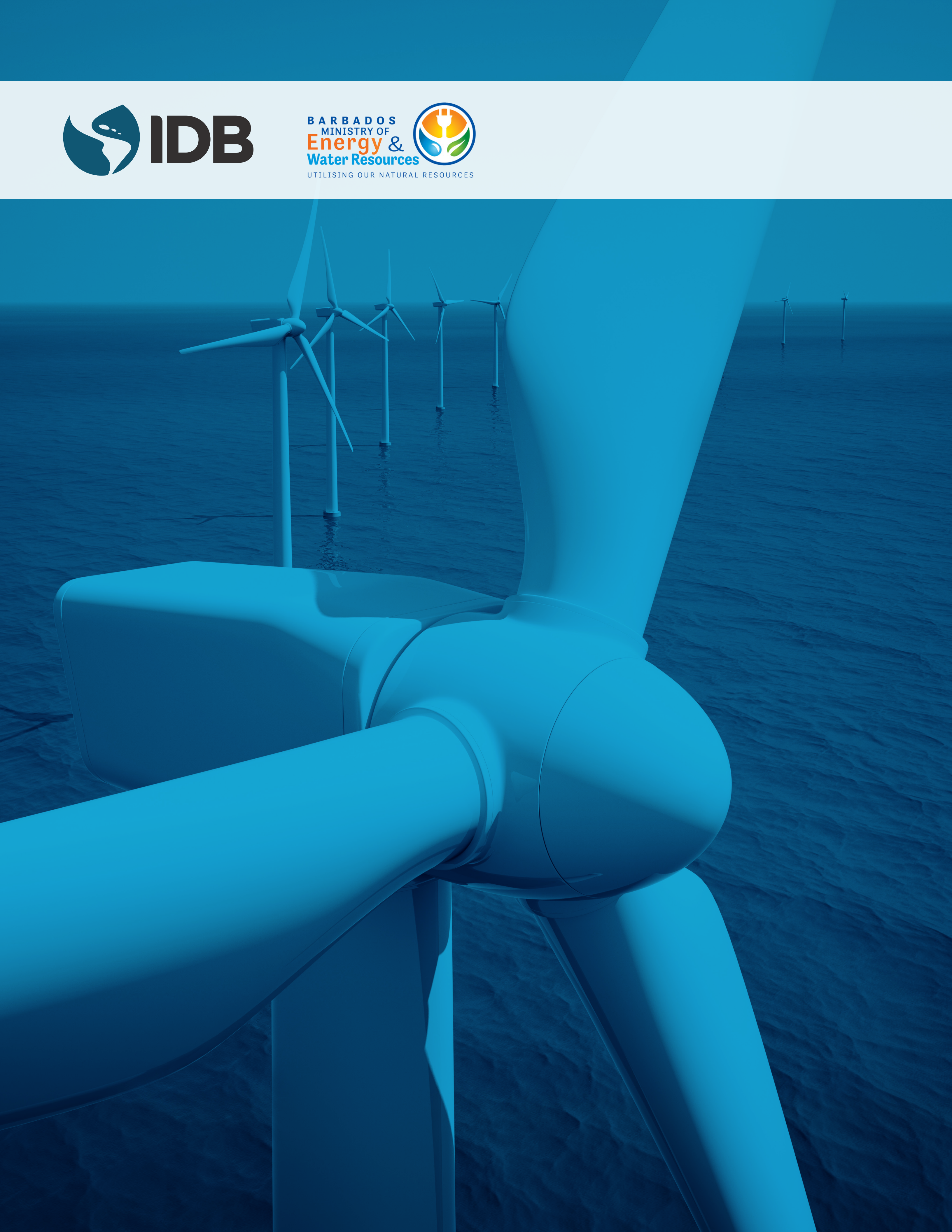
March 2020

Prepared by: Sweyn Johnston, John McGlynn & Veronica R. Prado

IDB

BARBADOS MINISTRY OF Energy & Water Resources

UTILISING OUR NATURAL RESOURCES



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/ EXECUTIVE SUMMARY

/ EXECUTIVE SUMMARY

This Technical Note has been commissioned by the Inter-American Development Bank with the purpose of presenting information on the operating principles and development status of selected Marine Renewable Energy technologies, and to assess the future potential for deployment in Barbados. The broad findings for each technology considered are;

Fixed Offshore Wind

Fixed Offshore Wind is well established as a commercial technology, and the offshore wind resource in Barbados is assessed as 'good', but the only potentially suitable deployment locations in Barbados are all within 3km from shore where visual impact will be significant and where other technical considerations pose challenges. Therefore the practical potential for this technology in Barbados is found to be limited.

Floating Offshore Wind

Floating Offshore Wind is a rapidly maturing technology with global market potential. The rate of deployment of the technology is forecast to increase rapidly and the sector is expected to reach commercial readiness within five years. The theoretical resource potential for conventional floating wind (in 60-200m water depth) in Barbados is estimated at 189MW, with over 8GW of potential for deep floating wind (in depths of 200-1000m). A number of very large areas potentially suitable for deployment of the technology have been identified. These areas are distributed to the south, west and off the north coast of the island with each area being of sufficient size to host a project of substantial scale.

Sea Water Air Conditioning (SWAC)

SWAC is identified as a promising but highly site-specific technology. The technology may be commercially viable at some locations at present however it is generally expected to reach general commercial readiness at a broader range of sites within five years. Barbados is a promising location for SWAC projects given the high cost of energy and substantial, year-round cooling requirement. There is a slight mismatch between areas with best access to deep water and areas likely to have most cooling demand and further work is required to identify suitable projects and assess overall feasibility.

Ocean Thermal Energy Conversion (OTEC)

OTEC is identified as a highly promising technology but is broadly anticipated to require more than five years to reach commercial readiness. The thermal difference between surface and deep waters in Barbados territorial waters is found to be suitable for OTEC plant. Numerous and extensive areas of interest for potential future project locations have been identified. The theoretical resource potential for OTEC is conservatively assessed as 160MW.

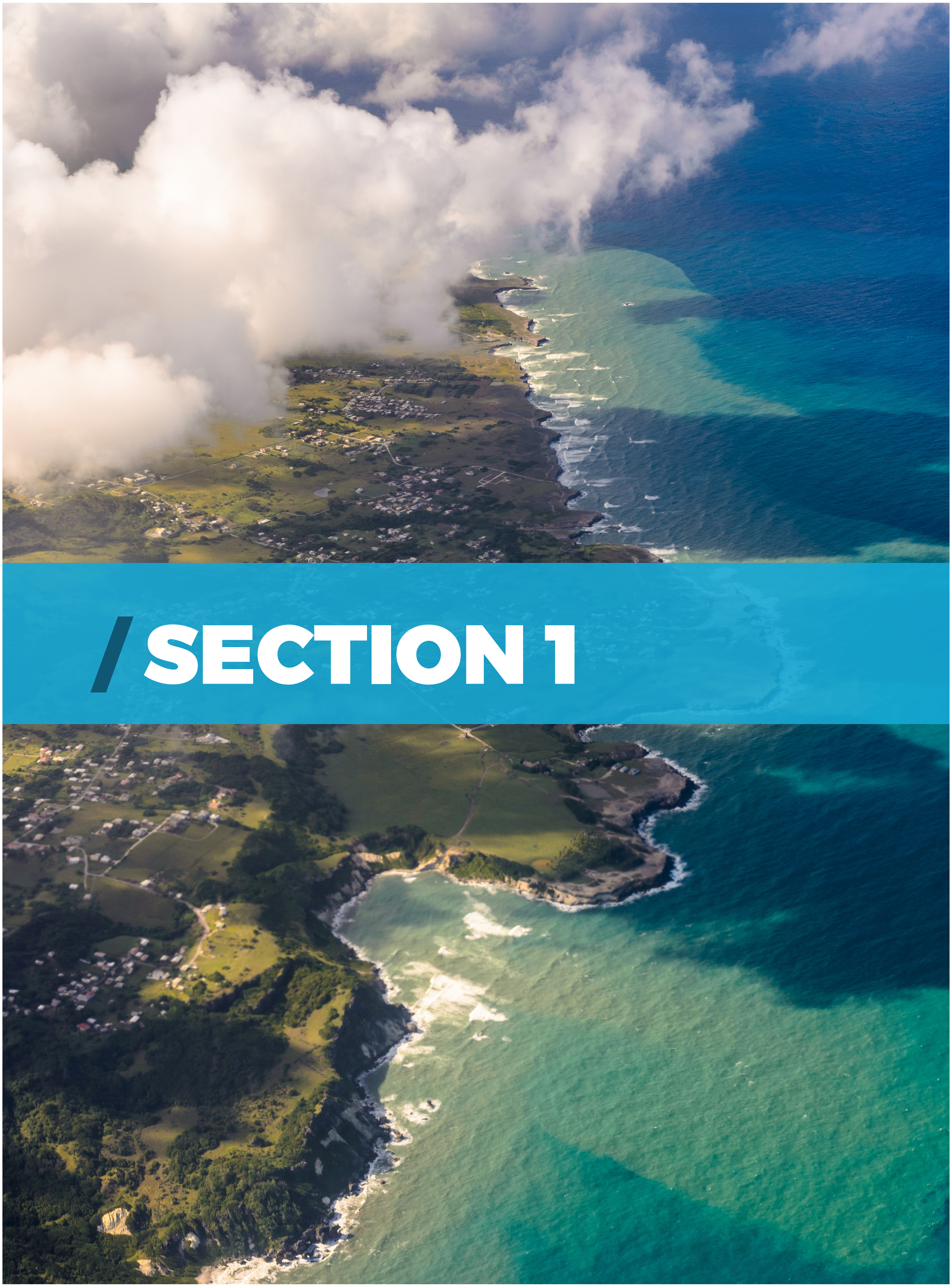
Wave Energy

Wave Energy is expected to take between five and ten years to reach commercial readiness. Barbados is considered to have a 'moderate' to 'good' wave resource and a number of potentially suitable development sites have been identified off the east coast.

Tidal and Ocean Current Energy

Tidal energy may be commercial within five years, however no potential development sites for this technology has been or are expected to be identified in Barbados. Ocean Current is much further from commercialisation than tidal (up to 10 years) and again no sites have been identified.

Overall, this report aims to engender a much improved understanding of the potential for marine renewable energy deployment in Barbados by matching resource potential with technical and commercial readiness. This is consistent with and will support the target of the Government of Barbados to fully decarbonise by 2030 as stated in its National Energy Policy 2019-2030



SECTION 1

/ INTRODUCTION

1.1. / INTRODUCTION TO MARINE RENEWABLE ENERGY AND ITS POTENTIAL FOR APPLICATION IN BARBADOS

The term 'Marine Renewable Energy' (MRE), also referred to as 'Ocean Energy' or 'Offshore Renewable Energy', describes a suite of related renewable energy technologies, as discussed in Section 1.2 below, which are deployed in the offshore marine environment where they operate by gathering energy and converting this to electricity. MRE technologies offer the potential for a secure, reliable supply of indigenous clean energy – this makes the sector particularly attractive and worthy of investigation for the Small Island Developing States (SIDS) including Barbados. The technologies which make up this emerging sector are at different stages of commercial readiness.

MRE technologies have largely been developed and are being proven in the industrialised nations of the northern hemisphere (such as the UK, Germany, China and the USA), but have global deployment potential. The technologies are also of particular relevance in Barbados where they may offer potential to address issues related to security of supply, carbon emissions and cost of energy. Fixed offshore wind (OSW) in particular has now become cost-competitive with conventional forms of electricity generation in many settings. Of the other technologies in the sector, Sea Water Air Conditioning (SWAC) offers the ability to utilise deep water close to shore to provide cost competitive cooling load to medium to large-scale industrial users. Related to this, although technically not as mature, Ocean Thermal Energy Conversion (OTEC), appears to offer a highly appealing combination of resource availability, scale and ancillary benefits. The floating OSW sector, while less technically mature than fixed OSW, has made rapid and steady progress towards global commercialisation and is a technology of enormous promise for the region.

Early high level work looking at the overall Theoretical Resource Potential for selected MRE technologies in Barbados (outlined in Table 1.1) highlights that these technologies have potential to provide many gigawatts of power, in a country where peak electrical demand is 155MW.

Table 1.1. Theoretical Resource Potential for selected MRE technologies in Barbados

Technology	Maximum Theoretical Resource Potential (MW)
Fixed OSW	0 (unless within 3km from shore)
Floating OSW (conventional)	189
Floating OSW (deep)	8,344
OTEC	160
Total	**8,693**

Note: Methodology for this analysis is provided in Appendix A

All of the above MRE technologies, once deployed, will contribute to the diversification of the energy mix, reduce reliance upon fossil-fuel imports, and by replacing demand with a local indigenous resource, will have an overall positive impact on the resiliency of the energy system and economy.

1.2. / BACKGROUND TO THIS TECHNICAL NOTE

This Technical Note is a standalone piece of work that has been commissioned by the Inter-American Development Bank (IDB) drawing upon and updating a previous body of work prepared by sector experts Sweyn Johnston and John McGlynn with support and guidance from IDB Energy Specialist in Barbados, Veronica R. Prado.

The core purpose of this Technical Note is to present information on the operating principles and development status, as well as to comment on the future potential for deployment in Barbados, of the following MRE technologies;

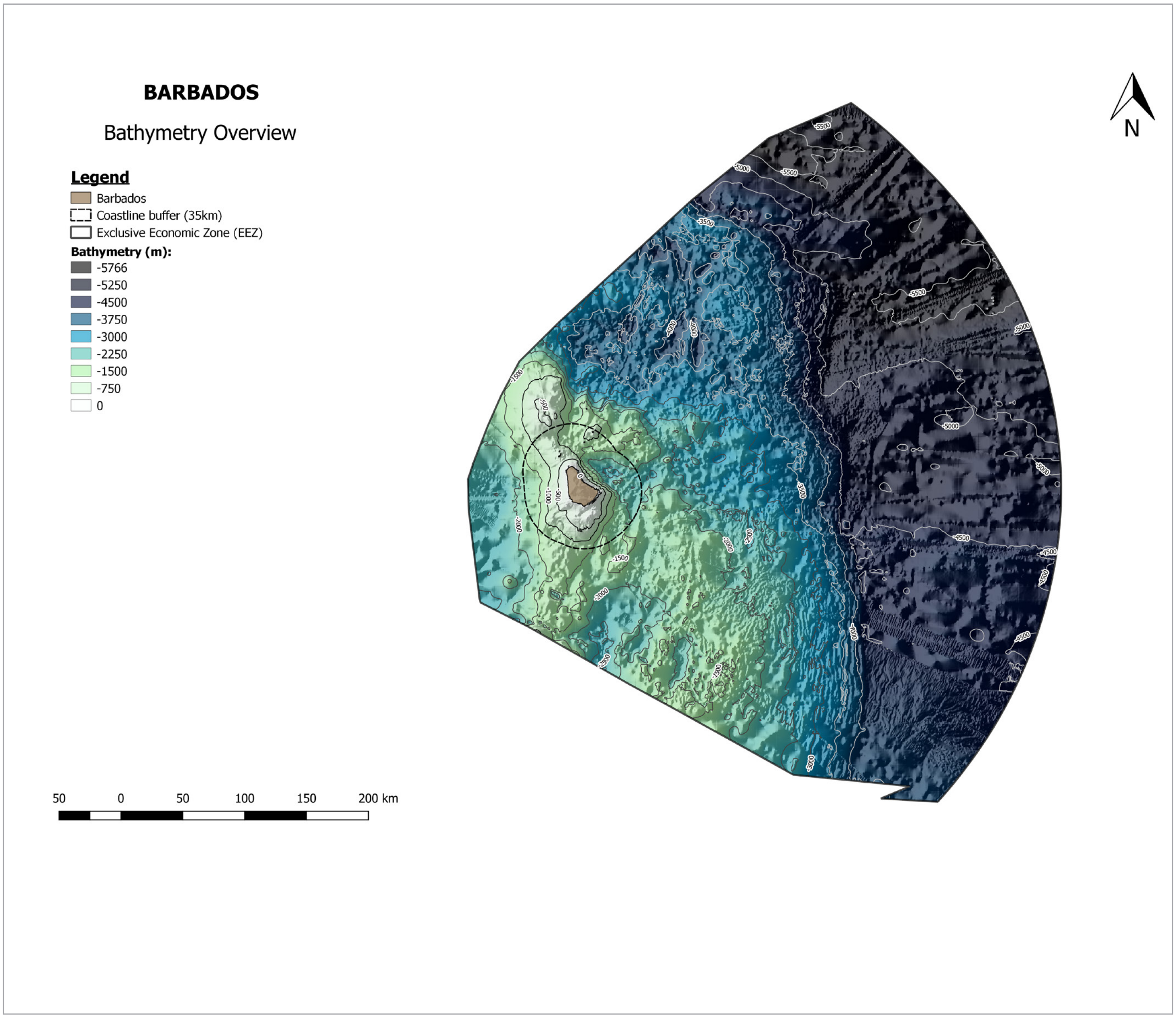
- Fixed offshore wind (Fixed OSW)
- Floating offshore wind (Floating OSW)
- Ocean Thermal Energy Conversion (OTEC)
- Sea Water Air Conditioning (SWAC)
- Wave energy conversion
- Tidal and ocean current energy conversion

Technology assessment work carried out in the production of this Technical Note is based on the latest industry intelligence backed up by information provided by leading technology developers themselves.

This document is an update and extension of work previously undertaken by the same sector experts for the IDB and Government of Barbados under the Public Sector Smart Energy Programme (PSSEP). Previous work carried out in Barbados has included a Technology and Project Review, commercial project development 'road mapping' and a detailed Geographic Information Systems (GIS) based marine mapping exercise to identify preferred offshore development sites. This work has provided a strong starting point for completion of a suite of more sophisticated technical, financial and environmental studies for which this Technical Note should be viewed as a precursor.

In terms of the geographic scope of this report, the Exclusive Economic Zone (EEZ) of Barbados, as shown in Figure 1.1, will be used to present resource graphics, except where limited by availability of data. Previous GIS Locational Guidance work used a more focussed geographic scope, within a distance of 35km from land based on a balance between availability of data, minimising impacts, and project economics at distance from shore. This Locational Guidance work underpins and will therefore direct the discussion on areas of interest identified.

Figure 1.1. Scope of study with bathymetry overlay



1.3. / STRUCTURE OF TECHNICAL NOTE

Each technology is considered in turn in the following sections using the following structure;

1. Operating principles:

- This aim of this sub-section is to provide the layperson with an understanding of the basic principles by which the various ocean energy technologies selected for inclusion in this report operate. It is therefore intentionally broad in scope and general in nature.

2. Development status:

- This section describes the current status of technology and project development for the selected MRE technologies. The current global status and major industry-leading projects in each technology sector are presented and summarised.

3. Operational requirements and resource:

- Broad consideration is given to operational requirements for each MRE technology, such as water depth and distance from shore, and a broad look at available resource in Barbados is considered.

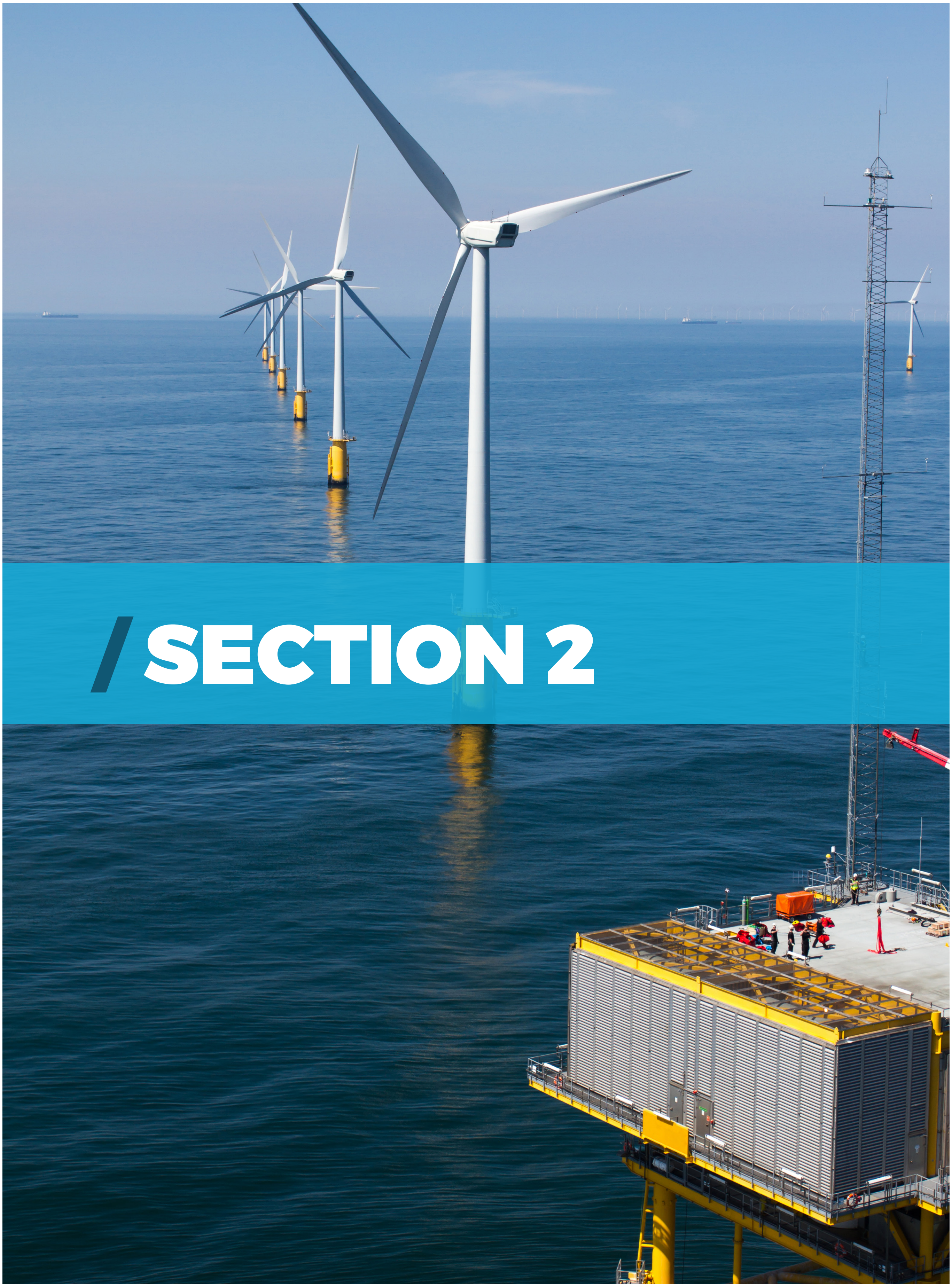
4. Locational Guidance:

- For Fixed OSW, Floating OSW, OTEC and Wave energy, results of locational guidance work are presented which, recognising limitations in availability of data, indicate the areas around Barbados likely to be most suitable for development. No formal locational guidance work has been undertaken for tidal, ocean current and SWAC but some discussion is provided.

5. Discussion:

- Technology readiness is considered against available resource in order to enable general assessment of the likely applicability of each of the selected technologies.

This is followed by a section which provides an overview to consider the merits of each technology option against each other alongside a discussion of the findings and general recommendations. Links to relevant industry reports are also provided. Detail on the methodology applied to calculate the Theoretical Resource potential for selected technologies is provided in Appendix A, whilst detail on the methodology applied for the previous GIS Locational Guidance study is provided in Appendix B.



SECTION 2

/ FIXED OFFSHORE WIND (OSW)

2.1 / FIXED OSW - OPERATING PRINCIPLE

Wind is created due to ever changing locational variations in atmospheric pressure driven by the difference in heating from the sun between the equator and the poles, and the rotation of the earth (Coriolis Effect). Wind energy devices harness these flows of air by converting it into rotational movement to drive an electric generator. Onshore wind generation is a well-developed industry and offshore wind essentially uses the same generation technology and pairs it with alternative foundation technology to secure the generator to the seabed and connect it to shore. The rationale for locating wind turbines offshore is to access a stronger and more consistent wind resource whilst also lessening the potential for visual impact and concerns relating to competition for land use.

Numerous concepts exist for connecting offshore wind turbines to the seabed. In shallow water this is often achieved using proven technology from other industries such as piling, jacket foundation or suction techniques. Examples of foundation systems used are outlined in Figure 2.2.

***Figure 2.2** Example foundation systems for fixed OSW*

Source: Adapted from NREL (2015).
Left to right: monopile, four-legged jacket, twisted jacket.

2.2 / FIXED OSW - DEVELOPMENT STATUS

Fixed OSW is a mature and well-understood technology with significant capacity installed. The first fixed OSW project was installed off the coast of Denmark in 1991, and commercial-scale installations have been in operation ever since. Offshore array deployment over recent years has been spurred by a variety of mostly revenue-based subsidy regimes. These have been effective in stimulating industry development and are now being phased out in leading markets, reflecting the maturity of the technology.

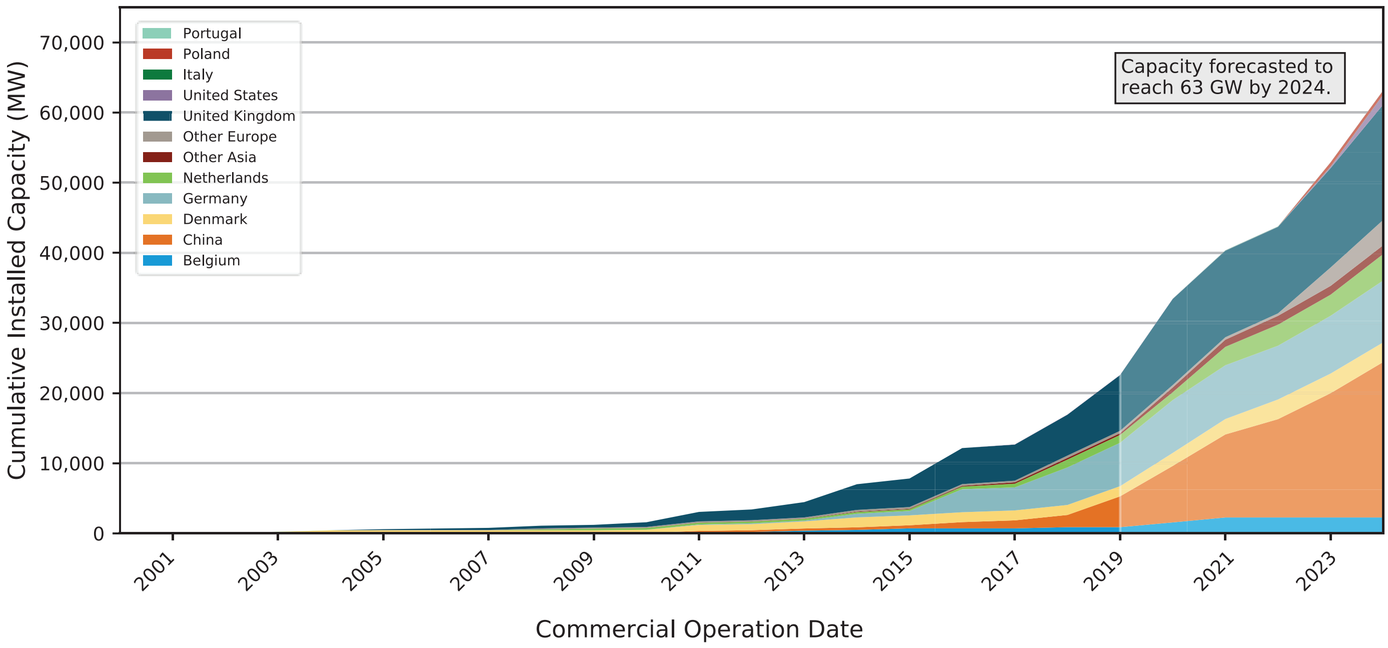
2.2.1 Global installed capacity & leading markets

China and Europe count for almost the entire global market. The majority of global OSW capacity is in Europe with 22,072MW installed at the end of 2019, with a total of 5,047 individual turbine units in operation across 12 countries. The UK has the largest amount of offshore wind capacity in Europe, accounting for 45% of all installations. Second is Germany with 34%, followed by Denmark (8%), Belgium (7%) and the Netherlands (5%) (WindEurope, 2020).

In the Asian market 2,652MW was installed in China during 2018 (most recent available data), more than anywhere else in the world, and 6MW was installed in Vietnam. Installed capacity in the USA at end-2018 stood at 30MW, with the entirety of this capacity accounted for by a single project located at Block Island, in the state of Rhode Island.

In terms of future projections, according to the US DOE (2019) Offshore Wind Market Report, a total of 44,000 MW additional capacity will be constructed in the period to 2024 (US DOE, 2019). This is illustrated in Figure 2.3 below.

***Figure 2.3** Current and projected future levels of OSW capacity by country*



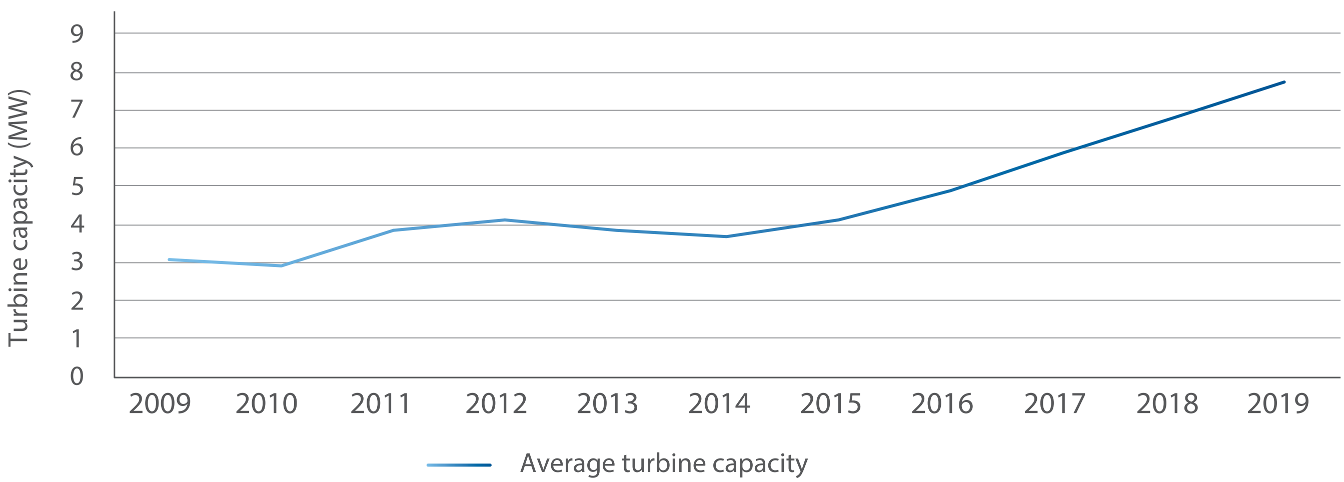
Source: US DOE (2019)

2.2.2 Turbine sizing trends

Fixed OSW turbines have to date shown a clear trend of increasing in size, as can be seen in Figure 2.4 below. This trend can be expected to be sustained as developers continue to compete and innovate in search of performance and cost improvements which can be achieved by increasing turbine size and capacity. The largest offshore wind turbine in the world, the V164-8.8 MW developed by MHI Vestas, was installed during 2018 at the European Offshore Wind Deployment Centre in Aberdeen, Scotland. Developers are expected to bring models to market with capacities of 10MW and above during the coming decade.

The average size of newly-installed offshore wind turbines in Europe in 2019 was 7.8MW, a 1MW increase on 2018. Since 2014 the average rated capacity of newly installed wind turbines has grown at an annual rate of 16%. Most fixed OSW farms under construction are now using turbines which are rated at 6MW or above (WindEurope, 2020).

***Figure 2.4** Average installed offshore wind turbine rated capacity (MW) by year*

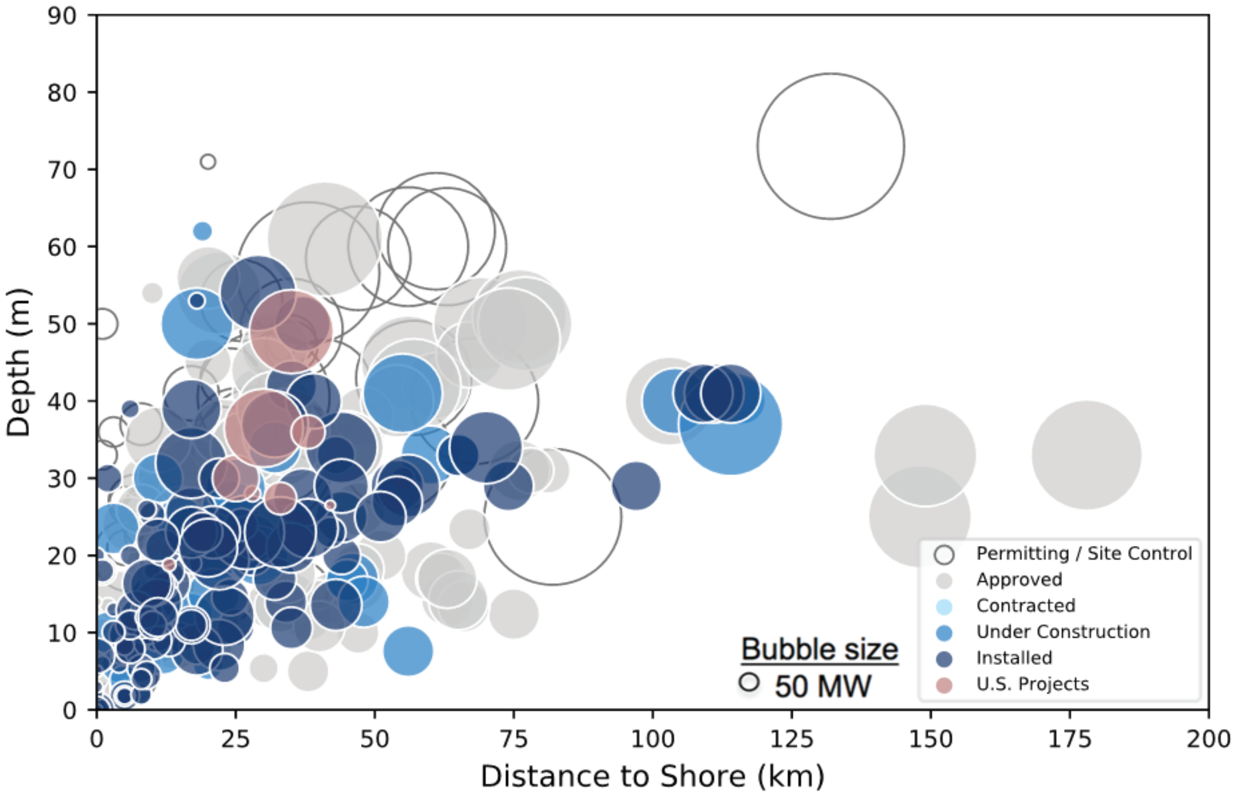


Source: WindEurope (2020)

2.2.3 Depth and distance from shore

As the Fixed OSW industry has developed there has been a reasonably pronounced trend in sites moving into deeper waters further from shore. There is however a relatively firm technical limit for installing fixed structures of around 60m water depth. Figure 2.5 below illustrates project size and distance from shore globally. The data shows that the tendency for projects to be installed in depths of 60m or less is set to continue, which is again due to practical limitations in installing in deeper waters.

Figure 2.5 Illustration of fixed OSW project depth, distance to shore and size



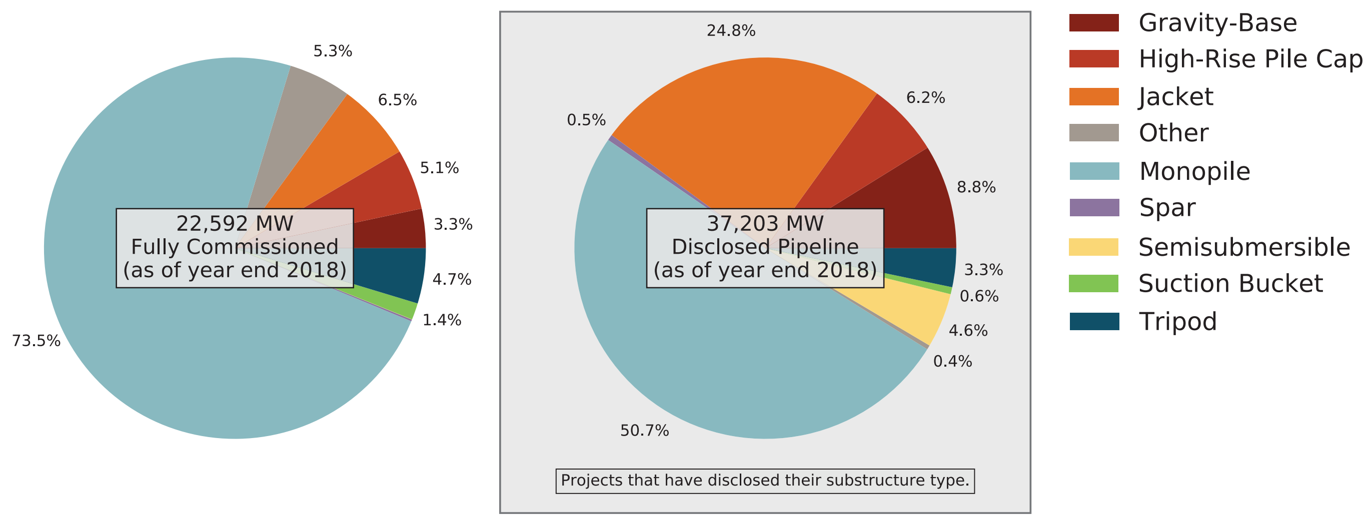
Source: US DOE (2019)

As can be seen in Figure 2.5 above, projects have tended to be sited within around 50km from shore. This limitation is economic rather than technical and some large projects are proposed at distances of over 100km from shore, taking advantage of developments in high-voltage DC technology.

2.2.4 Foundation types

Figure 2.6 below shows the types of foundation utilised in the industry to date. Monopile foundations account for over 70% of turbines installed globally. However other foundation types, in particular jacket solutions, are predicted to increase market share in the near future. The predicted shift away from monopile foundations can be attributed to the increasing technical maturity and reducing cost of alternative foundation types relative to monopile solutions.

***Figure 2.6** Current and projected share of foundation types utilised in the OSW industry*



Source: US DOE (2019)

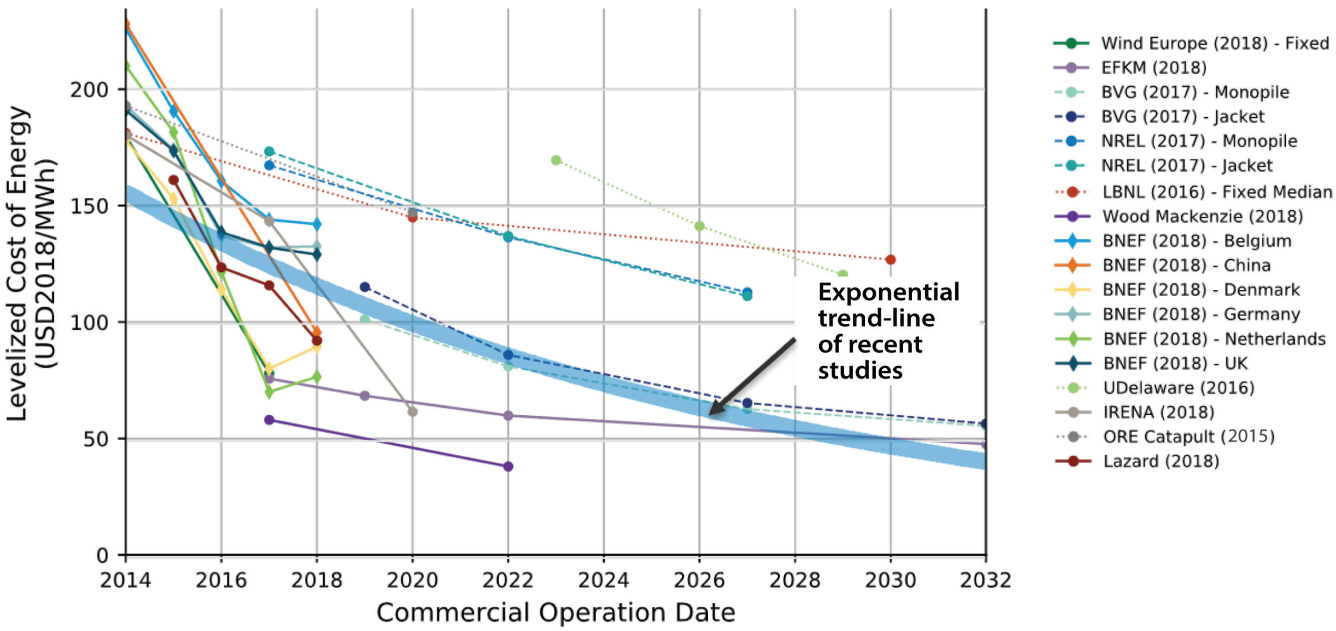
2.2.5 Cost trends

In 2018, the average capital expenditure for fixed OSW projects globally was estimated at $4.35 million USD per MW installed. For projects over 100MW commissioned in 2018, the range was $2.7-6.5 million USD per MW installed. The turbine element makes up about a third of this, with costs estimated at between $0.8-1.2 million USD per MW installed. Other capital intensive elements are turbine foundation and 'Balance of Plant' which essentially comprises the additional system elements required to connect the turbine to the electrical grid.

In terms of levelised cost of energy (LCOE), fixed OSW has seen dramatic reductions and recent auctions in Europe have delivered costs as low as $0.06/kWh. In China, which adopts a system of annual incremental subsidy reductions, the subsidy for fixed OSW projects has dropped from $0.12 in 2019 to $0.11 in 2020. These costs are significantly below what was thought to be achievable until recently, however, it should be noted that to give context to the figures stated above, both in Europe and China developers can bid in auctions before their projects are operational, and therefore many of the projects bidding into these auctions have yet to be built. Ever improving capacity factors also play an important role in reducing LCOE. In an October 2019 report the International Energy Agency referred to OSW as providing 'semi-baseload' power, as average capacity factors currently stand at around 45% and are predicted to increase beyond 50% and 60% as turbines become ever larger. Additionally, in further recognition of the consistency of the OSW resource, the IEA has also moved to reclassify OSW as a 'variable' rather than 'intermittent' renewable energy technology. It has stated that „Offshore wind's high capacity factors and lower variability make its system value comparable to baseload technologies, placing it in a category of its own – a variable baseload technology" (IEA 2019).

Figure 2.7 shows the overall industry trend and predicted trajectory in terms of LCOE using data compiled from numerous sources (as detailed below the table). This sees costs reducing to $0.05/kWh by 2030, although much of this reduction will relate to large projects demonstrating significant economies of scale.

Figure 2.7 Fixed OSW LCOE estimates and forecasts



Source: US DOE (2019)

2.3 / FIXED OSW – OPERATIONAL REQUIREMENTS AND RESOURCE IN BARBADOS

2.3.1 Operational requirements

The following criteria can broadly be assumed to be minimum requirements for a viable fixed OSW project:

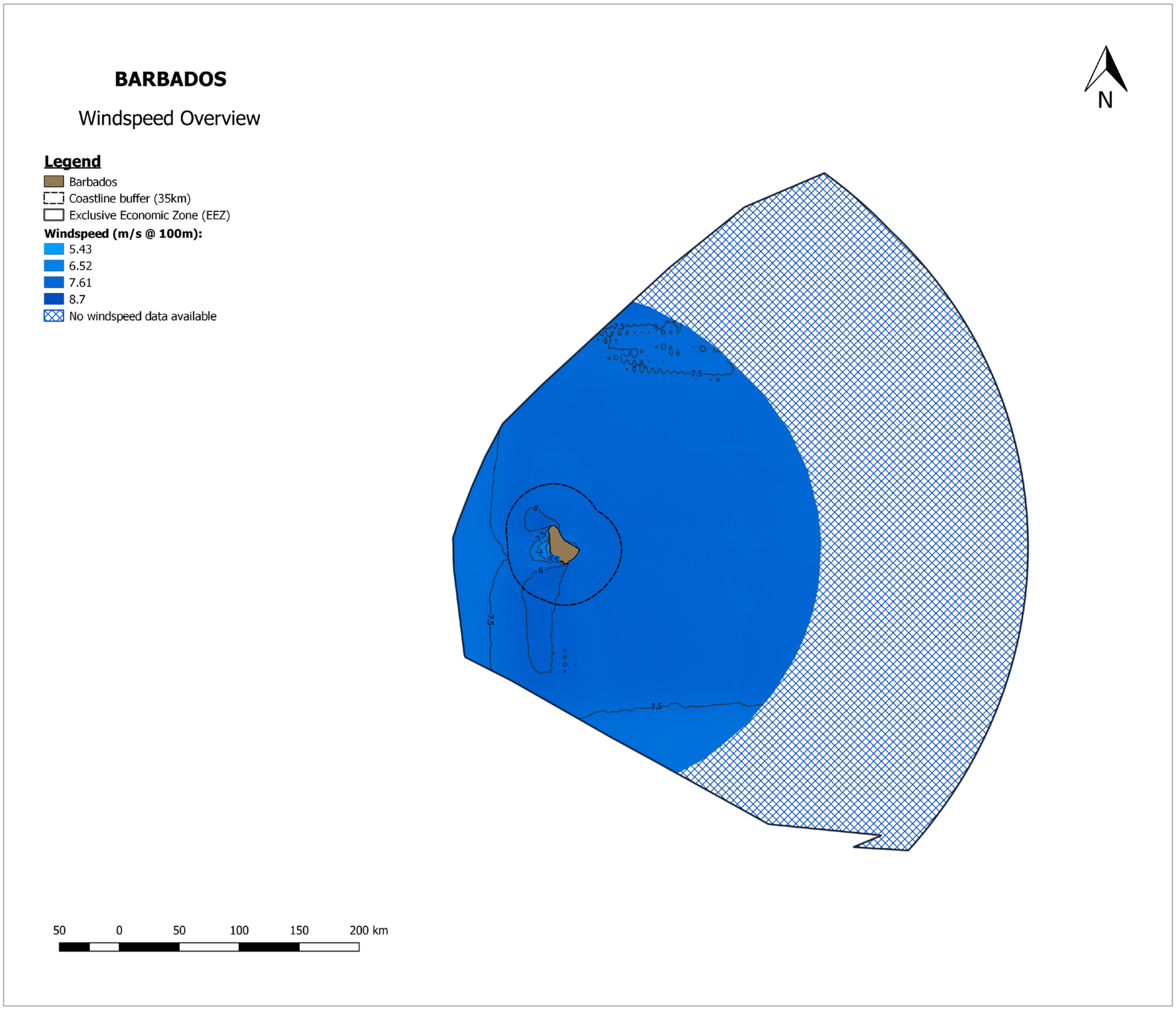
- **Wind speed:** A minimum mean wind speed of 5m/s (at hub height) is typically required for a project to be deemed to deliver an acceptable commercial return. A global geospatial analysis of OSW potential released by the International Energy Agency (IEA) in October 2019 excluded offshore areas with a mean wind speed below this threshold.
- **Depth:** Fixed OSW projects installed to date have been installed within a depth range of 10m – 60m with the majority of projects installed in depths of around 30m. Above 60m depth the additional cost and complexity of fixing the structure to the seabed means that floating structures become more technically and economically attractive.
- **Distance from shore:** Cabling costs increase as projects are located farther from shore. The cost of operating and maintaining arrays also increases in line with the distance to a suitable shore base. Larger projects which can bear these increased costs can be located further offshore than smaller projects but the cost implications in general remain. As a result of these factors, projects installed to date have tended to be relatively near-shore (average of 31km in Europe in 2018). Again IEA geospatial analysis (IEA, 2019) has applied a 60km limit for what it deems to be the 'nearshore' rather than the 'far offshore' extending to 300km.

- **Survivability / Design Suitability:** Onshore and offshore wind turbine technology developers offer a range of 'classes' of turbine to suit different deployment environments. Turbines should be appropriately suited to the environments in which they will operate – in terms of available wind speed, severity and frequency of extreme wind events and other factors and variables. One concern that exists regarding OSW deployment in the Caribbean (and also sub-tropical Asia) is the regular occurrence of extreme weather events such as earthquakes, hurricanes and typhoons. Hurricanes present challenges which differ from the regularly extremely windy conditions found in environments such as the North Sea, due to the severity of extreme winds, erratic and gusty conditions and associated storm surges. Turbine developers have begun to innovate in order to respond to these challenges. For example, MHI Vestas, a leader in the field, has recently announced the launch of a 9.5MW ‚Typhoon Class' turbine available in 2021. According to its developer the turbine can withstand wind speeds of up to 57m/s – equivalent to 205km/h. A category 3 hurricane exhibits sustained windspeeds in the range of 178km/h - 208km/h. Whilst hurricanes of category 3 and above are rare for much of the Caribbean region and very rare in the case of Barbados, this will remain a critical consideration in identifying suitable sites for OSW projects. This is especially important given the link between climate change and potential increases in the severity and frequency of tropical storms and hurricanes in the region combined with potential changes in predominant hurricane trajectories.
- **Geotechnical Considerations:** Large OSW turbines, including tower, blades and nacelle, can weigh in excess of 1000 metric tons. The localized seabed geology must be capable of supporting the weight and associated loadings of such a structure, although the choice of type of foundation can be tailored to suit the conditions to an extent.
- **Supply Chain and Maintenance Considerations:** Specialist heavy lift and 'jack up' vessels are required to install fixed OSW turbines. A cable laying vessel will also be required. These vessels are expensive and are generally in high demand. Suitable port and hardstanding facilities are also of importance during the construction phase. A fleet of smaller and less specialized vessels, with suitably qualified personnel, will be required to operate and maintain an array.

2.3.2 Fixed OSW Resource in Barbados

A broad assessment of the offshore wind resource in Barbados can be made using modelled data produced by the Global Wind Atlas (2019), see Figure 2.8. This shows average wind speeds at 100m hub height (a standard assessment metric for the wind energy industry) to a distance of 200km from land.

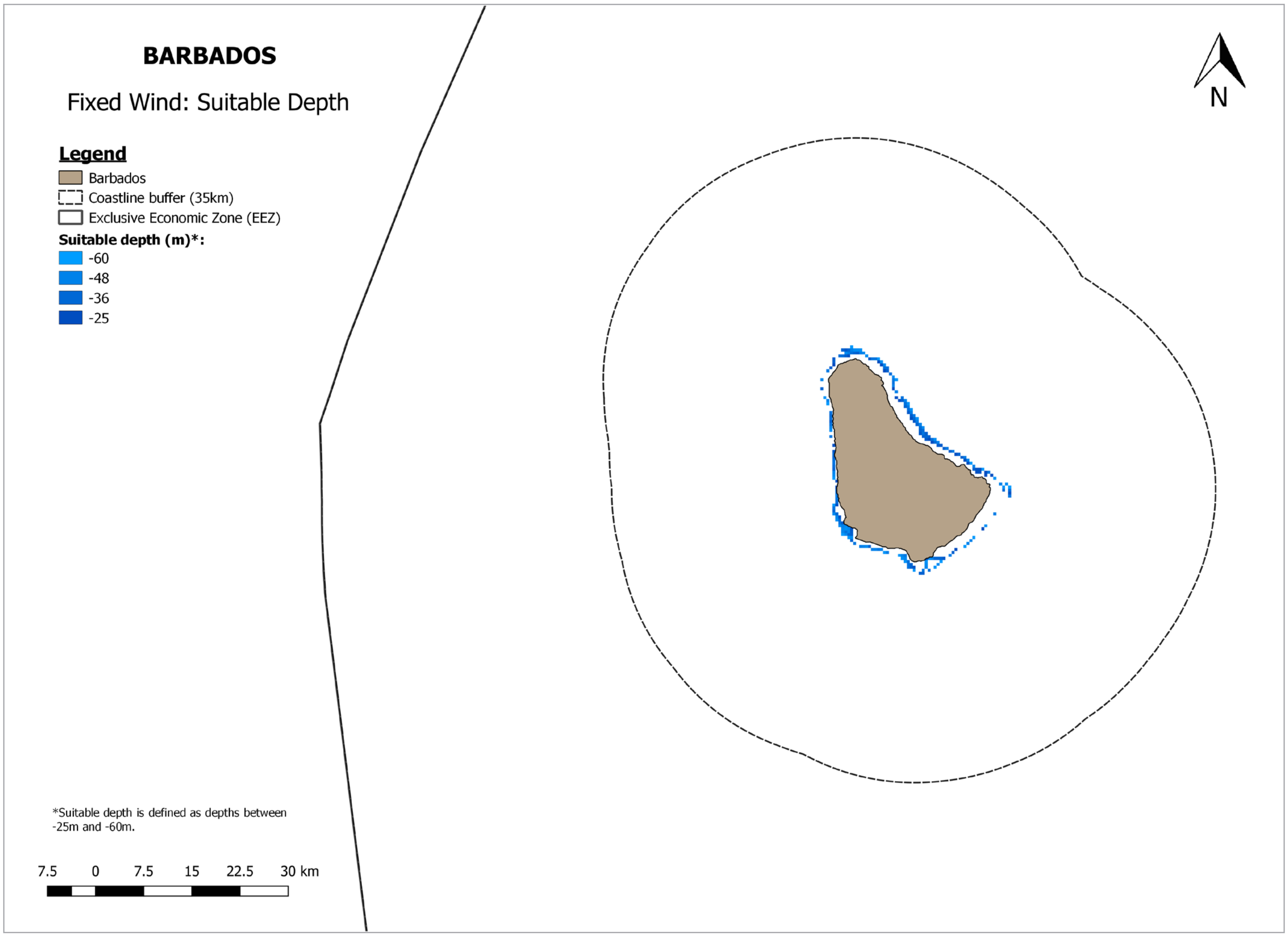
Figure 2.8 Average wind speeds within 200km of land at 100m height



Global Wind Atlas data indicates that mean wind speeds at 100m in the offshore sea space surrounding Barbados generally range between 6.5m/s and 8m/s – excluding a small area to the immediate west of the island physically 'shadowed' from the prevailing wind direction. Therefore the OSW wind resource in Barbados can be classified as being of a 'good' level with strongest wind speeds in evidence to the north of the island with a moderate land shadowing effect to the west.

Looking at suitable sea depths for fixed OSW in Barbados (Figure 2.9) it is apparent that potential is highly restricted by steep bathymetry and the transition to deep waters very close to shore for much of the nearshore space of the island. Some areas of suitable depth do exist close to shore as discussed further in Section 2.4.

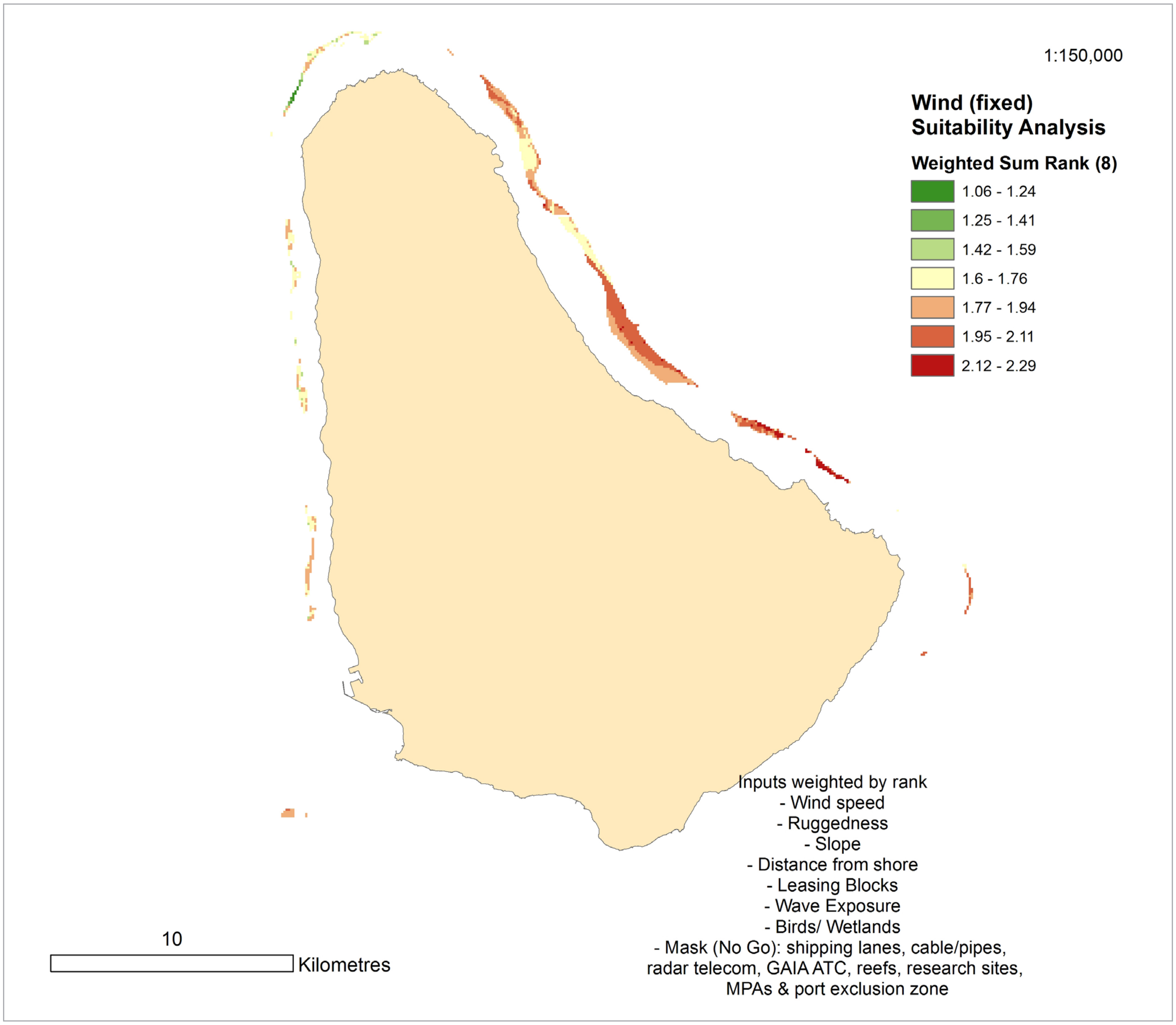
Figure 2.9 *Barbados: areas with suitable sea depth for fixed OSW*



2.4 / FIXED OSW – LOCATIONAL GUIDANCE

Figure 2.10 below presents the results of detailed locational guidance analysis with respect to fixed OSW undertaken with use of GIS software. This exercise was conducted across each of the technology types by 'layering' a number of resource and sea use datasets with the aim of identifying areas likely to be most suitable for development of a commercial ocean energy project. Further detail on the methodology utilised in this work is provided in Appendix B.

__Figure 2.10__ Fixed OSW - Weighted sum suitability analysis map



The Locational Guidance exercise for fixed OSW identified limited areas potentially suitable for deployment of the technology. The key limiting factor is suitable depth, with areas below 10m and above 60m deemed unsuitable and therefore excluded. In practical terms, this shows that any fixed OSW project would need to be located in close proximity to shore (within a few km). Such proximity to shore could be beneficial in terms of project costs, but would mean that any project would be highly visible from land. Whilst there is theoretically space for a meaningful scale of project, the opportunities for optimisation of site are highly limited due to the narrow band of suitable sea depths. The weighted scoring shows no large high scoring areas, with a strip of sea to the north east nominally identified as most promising. The larger areas on the east coast are lower scoring, largely due to increased wave exposure.

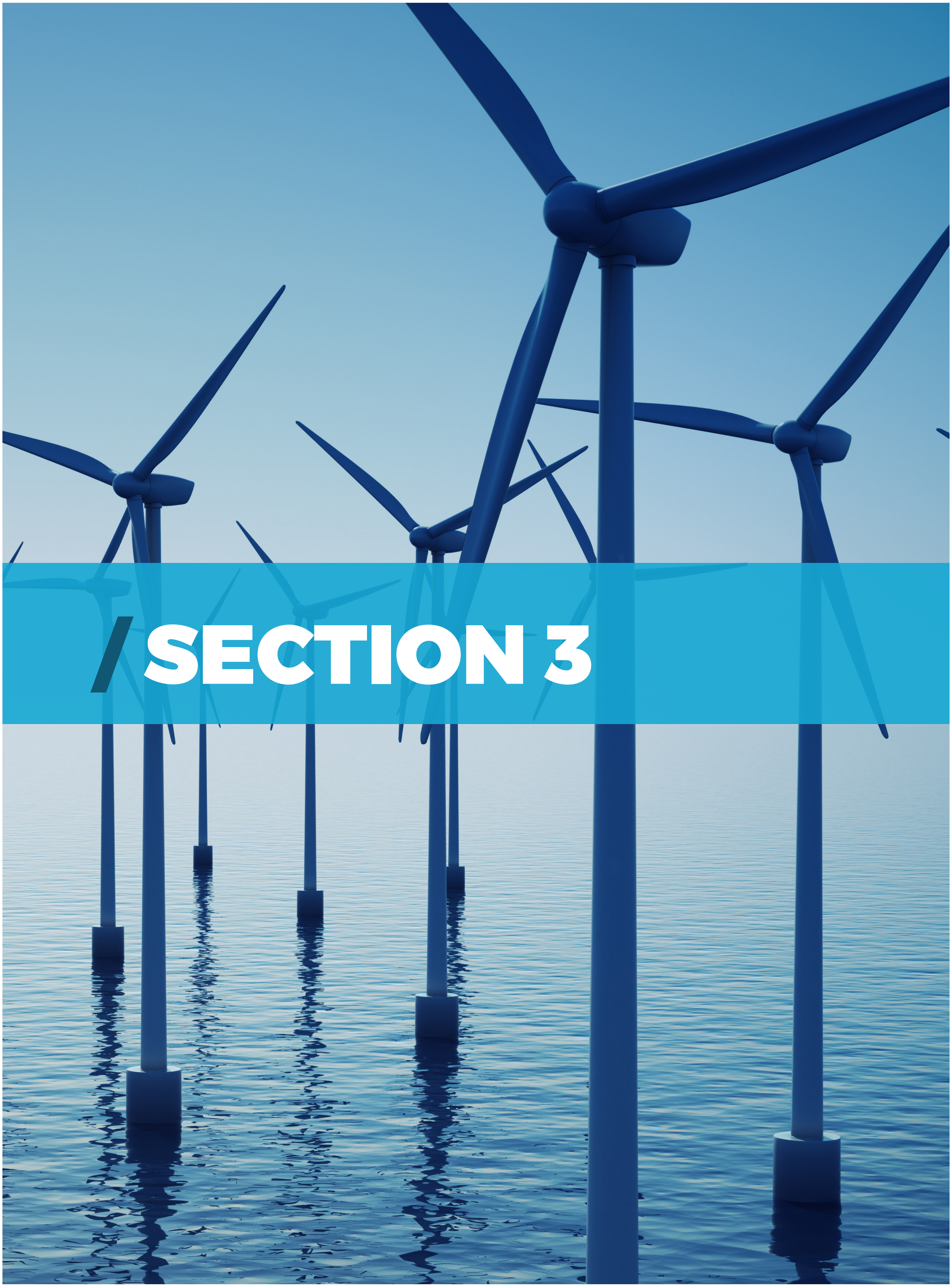
2.5 / FIXED OSW - DISCUSSION

In terms of commercial readiness, the technology for fixed offshore wind turbines has been rolled out on a commercial basis at a significant scale in Europe and Asia for a number of years and the industry continues to expand rapidly, including a significant pipeline of projects in the US. At the time of writing, there are no known commercial projects in the detailed planning stages in either Latin America or the Caribbean despite the definite coexistence of the suitable resource and market conditions in a number of locations in the region. A 5MW pilot offshore wind demonstrator project is however being planned for deployment off the north coast of Brazil in 2021 (IDB, 2019). This project would be the first instance of deployment of the technology in the region.

It is notable that the LCOE from fixed OSW projects has reduced sharply and recent projects have shown prices as low as $0.06 USD/kWh. This cost reduction is however largely driven by and linked to economies of scale and the ready availability of an advanced and highly competitive supply chain. Considering the overall relatively low level of electricity demand in Barbados, it would be challenging in the near to medium term to deliver the scale required to achieve LCOE levels seen in larger markets elsewhere.

While the quality of the wind resource in Barbados can be considered to be attractive, the potential for development of fixed OSW in the country appears to be substantially restricted due to a lack of areas of suitable sea depth. Some areas of suitable depth have been identified to the east of the island; however, these are likely to present significant challenges to fixed OSW project development. Firstly, these areas are located very close to shore (circa 1km – 3km) and any turbines installed in these areas would be highly visible from land. Secondly, the areas identified exhibit a steeply descending seabed which could be susceptible to issues in physically installing fixed bottom structures. Additional geotechnical factors such as ruggedness and substrate type were beyond the scope of the exercise but would also need to be considered. Thirdly, these areas are located either in, or very close to, a proposed Marine National Park, necessitating careful consideration of any impact on the park and its protected features and wildlife. Lastly, grid infrastructure on the east coast of Barbados is underdeveloped when compared with areas on the west and south coasts, which indicates higher complexity and cost in integrating any project into the grid.

Based on the above it is clear that the potential for fixed OSW in Barbados is restricted to areas in close proximity to shore and, due to practical considerations, is likely to be very limited overall. If a fixed OSW project was to be considered then a large amount of physical data collection and consultation would be required to determine if a suitable location can be found.


/SECTION 3

/ FLOATING OFFSHORE WIND (OSW)

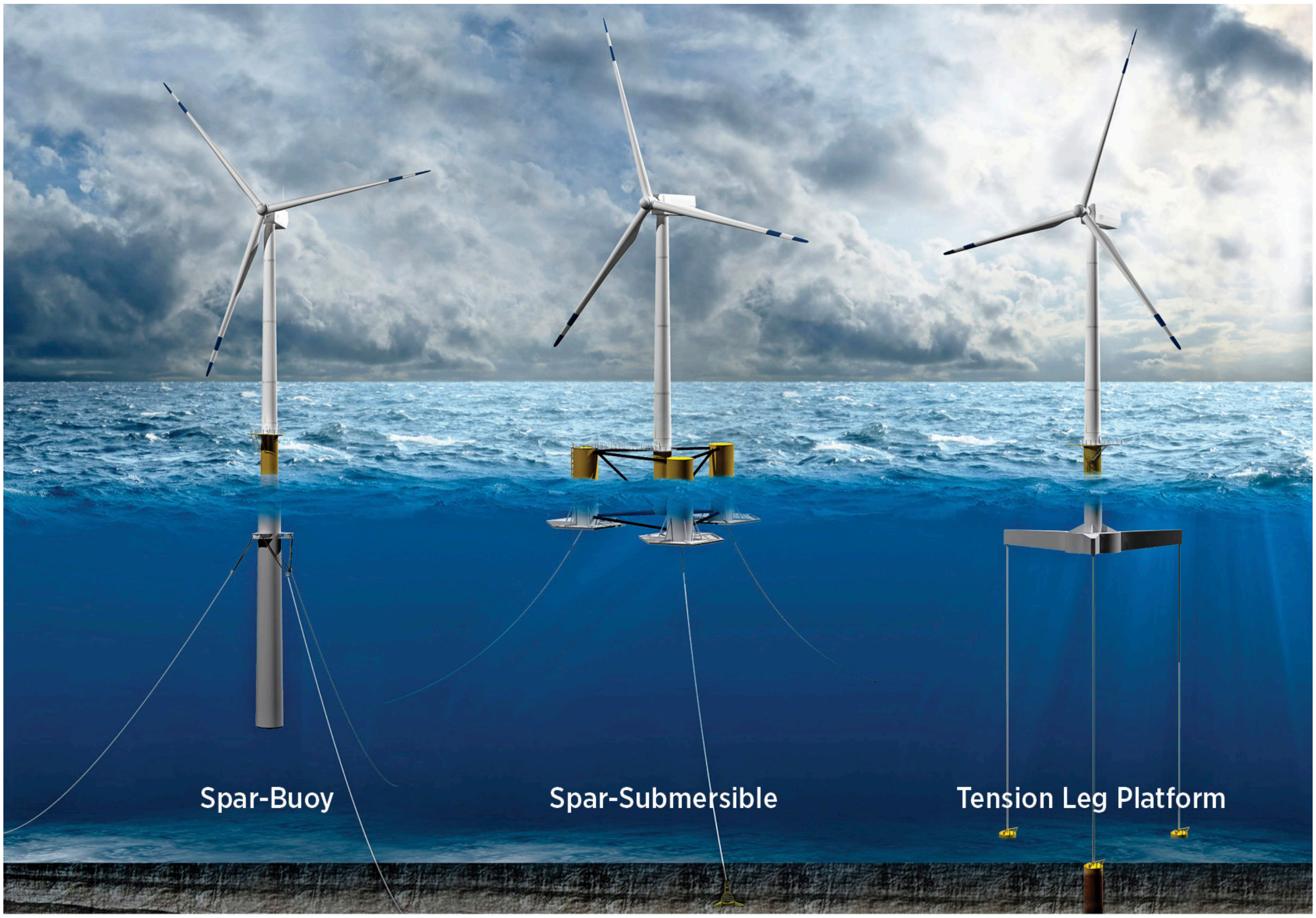
3.1 / FLOATING OSW - OPERATING PRINCIPLE

The operating principle for floating OSW is the same as for fixed OSW (outlined in Section 2.1) except that rather than having a direct weight bearing connection to the seabed, the turbine is installed on a floating structure, which in turn is attached to the seabed via mooring lines. This arrangement facilitates installation in much greater depths of water where, in theory, only additional mooring chain and cable are required to achieve this.

The turbine technology is therefore the same as fixed OSW and indeed all floating turbines installed to date have been designed for fixed projects. Beyond the turbine element, some consideration is required for floating turbines to take account of how the movement of the platform (which is only moored rather than solidly fixed to the seabed) can create additional forces or loads on the equipment and anchoring system. Numerous concepts exist and have been tested for the floating platform and mooring elements of the technology. These tend to utilise well understood technologies and methodologies adapted from the offshore oil and gas industry.

Examples of some platform and mooring systems are outlined in Figure 3.11. Because floating OSW can be installed in deeper waters the technology opens up new markets for development, can aid in accessing better wind resource, can further lessen the potential for visual impact, and further mitigate concerns relating to competition for land use.

Figure 3.11 Example foundation systems used for Floating OSW



Source: Adapted from IRENA (2016).

3.2 / FLOATING OSW - DEVELOPMENT STATUS

The floating OSW sector is at an earlier stage of development than the fixed OSW sector, but the overall market potential is arguably much greater because floating OSW offers the potential to open up new markets and sites in deeper water with less favourable geotechnical conditions which cannot readily be accessed using fixed wind technology.

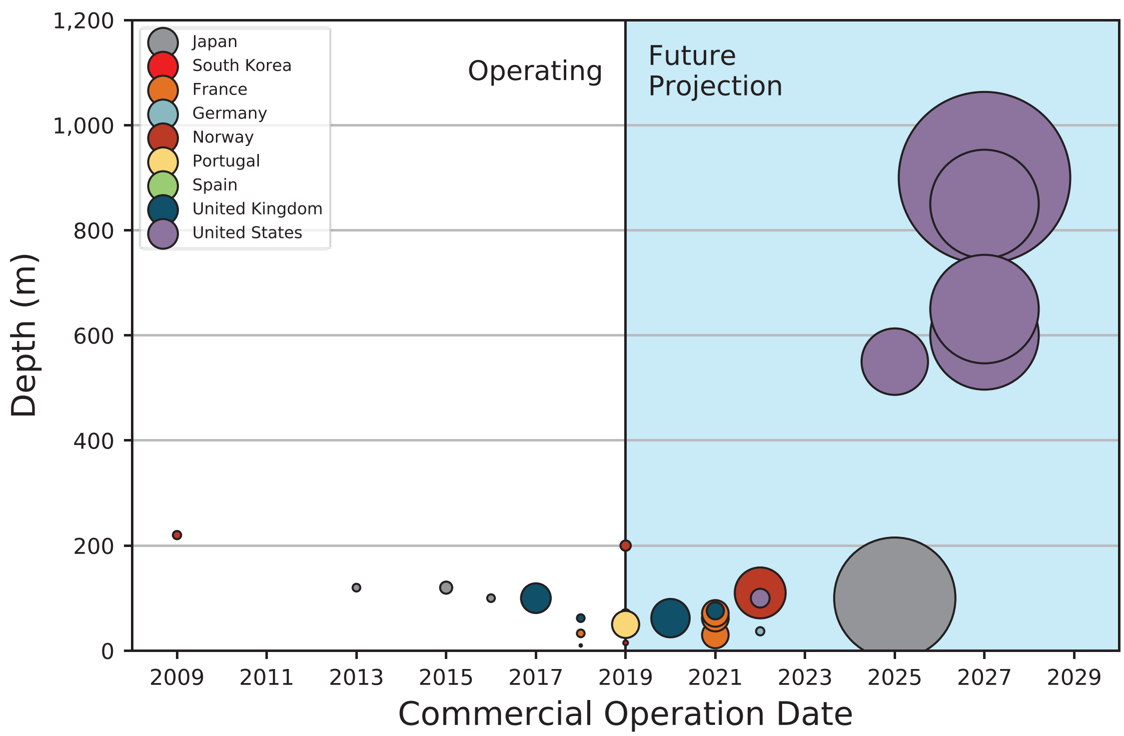
Research into floating OSW technologies for deeper water sites began in the mid-1990's. Floating OSW technologies are approaching commercial readiness but are still in a pre/semi-commercial demonstration phase. A number of individual full-scale prototypes have been successfully installed alongside the first array projects. Due to the ongoing success and commercial maturity of fixed OSW, it can reasonably be assumed that the floating OSW sector will continue to experience rapid technical development and progress to date has reinforced this assertion. Key elements related to the development status are discussed below with an assessment of the timeframe for commercial readiness of the technology provided in Figure 8.28.

3.2.1 Global installed capacity & leading markets

The floating OSW industry has been in steady development over the last five years or more, such that there are now eight floating wind projects installed globally with 46 MW of total capacity; five projects (37 MW) are in Europe and three (9 MW) are in Asia with the six-turbine 30MW Hywind project in Scotland the largest operational project at present. In addition, there are 14 floating projects totalling about 200 MW that are under construction or have achieved either financial close or regulatory approval. For further detail please see the US Department of Energy Offshore Wind Technologies Market Report, published in 2018, which provides a comprehensive information including list of recently installed OSW projects. (US DOE, 2019)

The global floating OSW pipeline has expanded rapidly in recent years with approximately 4,888 MW of capacity, growing by 2,000 MW relative to the pipeline as calculated in 2017 (US DOE, 2019). Installations to date and global pipeline for floating OSW are depicted in Figure 3.12.

Figure 3.12 Global Floating OSW installations and pipeline



Source: US DOE (2019)

Interestingly, floating OSW developments are not solely focussed on supplying electricity to the grid, and access to deeper sites further offshore means that floating wind is gaining interest from oil and gas companies looking to plug into renewables to reduce costs and carbon footprint from offshore production facilities. The 88MW Hywind Tampen project 140km offshore from Norway in 300m of water is an example of such a project for which financial close has been reached and construction contracts have been awarded (Equinor, 2019).

3.2.2 Turbine sizing trends

To date, all turbines used in floating OSW projects have been designed for fixed OSW as the market size has not been sufficient to stimulate development of specific, fully optimised floating models. That said, there is now a significant pipeline, and manufacturers are understood to be undertaking advanced development work towards commercially ready floating models, with a reduction in overall system weight likely to be desirable. There is not enough market information to assess turbine size trends in any detail; however, the same imperative to increase the number of MWs on each foundation exists and it can be expected that the market will drive for ever larger turbines. The only array project installed at present uses 6MW turbines, roughly in line with the fixed OSW industry standard.

3.2.3 Depth and distance from shore

Figure 3.12 in Section 3.2.1 shows that the vast majority of floating OSW projects are proposed at depths of less than 200m, although some large projects in the US are proposed at up to 1000m depth. The technological feasibility of installing in deep waters is largely not in question as the oil and gas industry has been installing structures such as Floating Production, Storage and Offloading (FPSO) platforms in very deep water in for many years. However installing in such depths, whilst opening up new markets, will have an associated cost penalty. Interestingly, sites which are overly shallow can also be problematic for large floating structures as these are generally 'slack' or catenary moored in order to provide passive load dampening. Taut moored systems, using shorter mooring lines, do not tend to be favoured for mooring of large floating structures in energetic environments.

There is no information available as regards the distance from shore at which developers intend to locate proposed floating OSW projects; however, it is likely that similar economic and practical constraints to fixed OSW projects will exist. This means that whilst there are no insurmountable technical barriers to going farther offshore, doing so will come at a financial cost as installation, interconnection and operations will be more challenging and time consuming. Analysis of the fixed OSW industry showed that most projects stayed within 60km of shore. Significant economies of scale (i.e. very large projects) are likely to be required for an OSW project, either fixed or floating, to make sense at greater distances, unless purposed to supply power to offshore oil and gas assets.

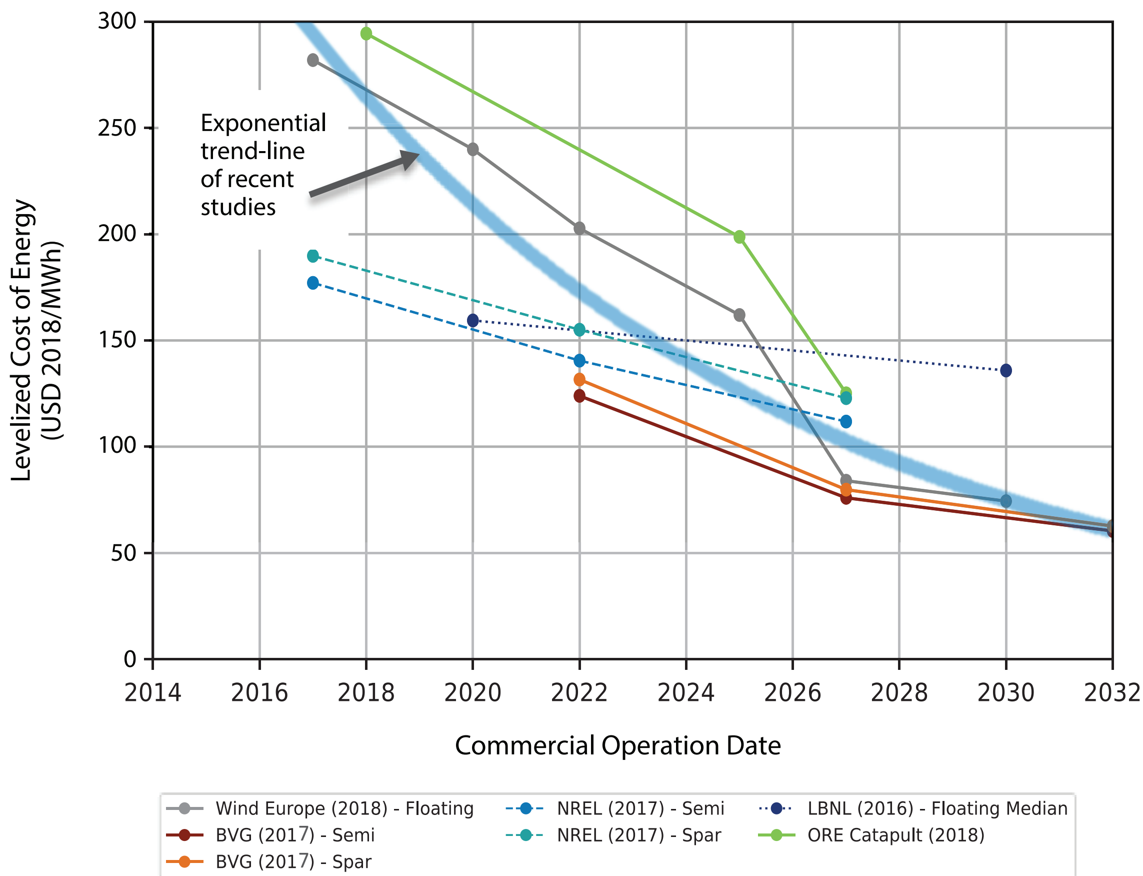
3.2.4 Foundation trends

Of the various platform types for floating OSW more than 90% of projects in the pipeline propose using semisubmersible technology (US DOE, 2019). This technology appears to be favoured due to its familiarity and the benefit that turbines can be installed on the substructure close to shore in relatively shallow water, before being towed out to shore, avoiding the need for heavy lift offshore construction vessels. This is more challenging for other platform types, such as spars, which require a much greater depth of water to float. That said, the largest existing project (the 30MW Hywind project in Scotland) does use spar platforms, and spar technology is projected to continue to be used in selected instances in the future. Platforms are generally fabricated from steel although concrete structures have also been used and are touted by some technology developers as offering cost reduction potential in serial production.

3.2.5 Cost trends

As shown in Figure 3.13, floating OSW LCOE was estimated at around $0.17/kWh in 2018 and is predicted to reduce to $0.07/kWh by 2030 (US DOE, 2019). This level of strong cost reduction will make floating OSW highly cost competitive with other forms of renewable energy. Due to the relatively nascent nature of the industry no further breakdown of CAPEX or operational costs is available.

Figure 3.13 Floating OSW LCOE estimates and forecasts



Source: US DOE (2019)

3.3 / FLOATING OSW – OPERATIONAL REQUIREMENTS AND RESOURCE IN BARBADOS

3.3.1 Operational requirements

The following criteria can broadly be assumed to be minimum requirements for a viable floating OSW project. These are largely similar to fixed OSW with some important exceptions.

- **Wind speed:** As with fixed OSW, a minimum mean wind speed of 5m/s (at hub height) is typically required for a project to be deemed to deliver an acceptable commercial return. Floating OSW projects are installed in deeper waters than fixed projects where the wind resource will usually be stronger. As per Figure 2.8 analysis of the Global Wind Atlas data (Global Wind Atlas 2019)_indicates that the mean windspeed offshore of Barbados at 100m hub height is generally between 6.5m/s and 8m/s – which can be considered an attractive to very attractive although not outstanding resource in global terms.
- **Depth:** Floating OSW can be deployed in depths of 60m or greater where fixed OSW is no longer technically feasible. Projects can be notionally split into 'conventional' installed in depths of up to 200m and 'deep water' installed in depths of 200m – 1000m. Most developers are focusing on conventional projects to prove their technology; however, a handful are directly targeting deep water markets – such as Japan and island groups including Hawaii – in an effort to gain first-mover advantage over competitors.
- **Distance from shore:** Cabling costs for fixed and floating OSW projects are much the same. Most projects, with the exception of the very largest which will utilise HVDC technology, will be classified as 'nearshore' in that they will be situated within a reasonable distance from shore of 60km or less.
- **Survivability / Design Suitability:** Offshore wind turbine developers have begun to develop innovative models which can withstand extreme wind events. Extreme winds and storm surges present additional challenges for anchored floating structures offshore which have yet to be fully resolved. These issues generally vary by site and will be addressed by the project developer. The first mitigating action will always be to carefully site projects to minimize exposure.
- **Geotechnical Considerations:** Large floating OSW turbines plus foundations can exceed the weight of fixed OSW variants which in themselves can weigh in excess of 1000 metric tons. Although floating turbines are not directly in contact with the seabed, local conditions must be conducive to reliable anchoring of such structures.
- **Supply Chain Considerations:** Whereas specialist, in demand heavy lift and 'jack up' vessels are required to install fixed OSW turbines, this is not necessarily likely to be the case for floating OSW. Floating structures can potentially be assembled either on land or just offshore and be towed to site using a suitable, albeit still specialist, vessel – this is likely to provide some cost savings when compared with fixed OSW. As with fixed OSW, a fleet of smaller and less specialized vessels, with suitably qualified personnel, will be required to operate and maintain an array.

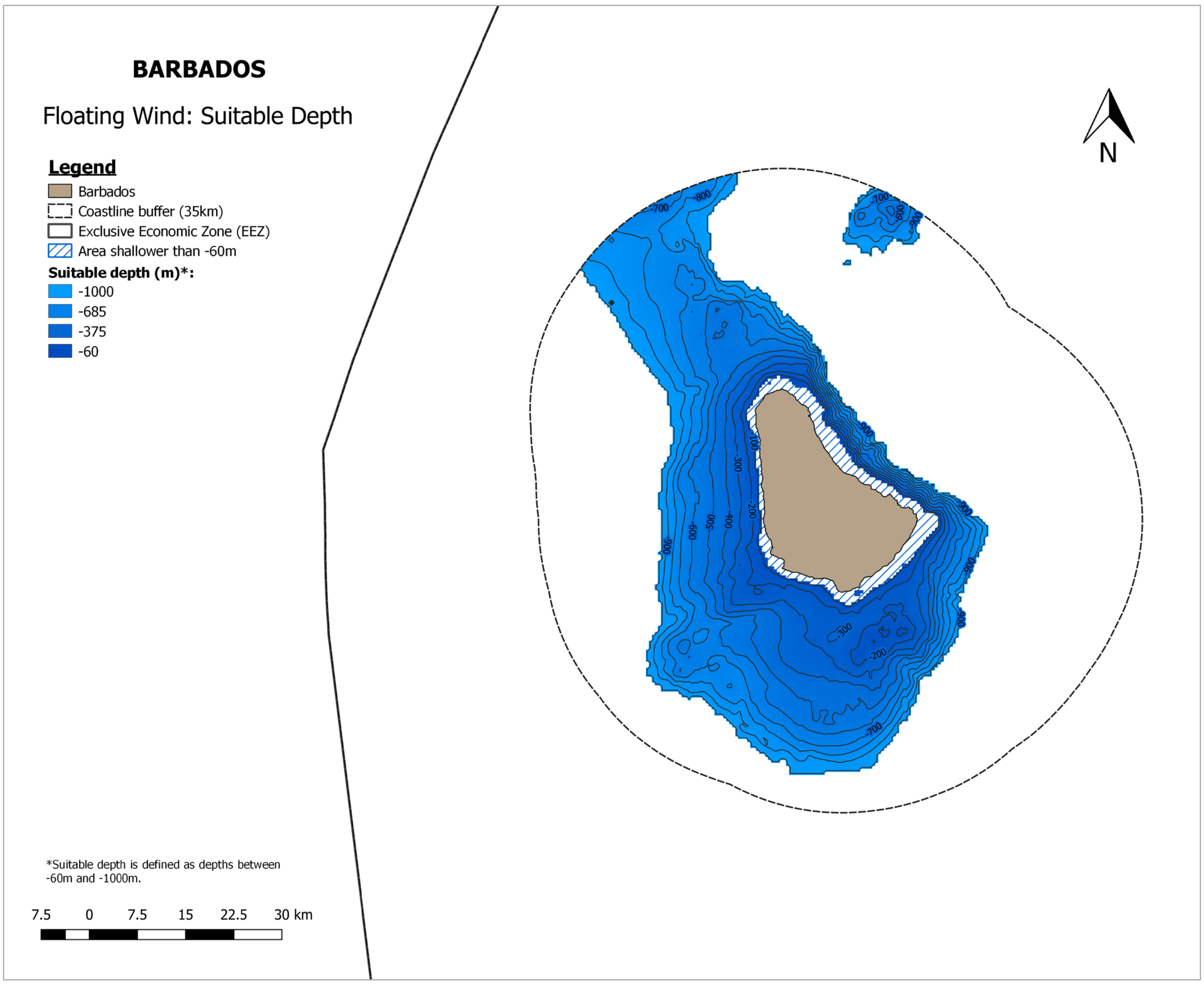
3.3.2 Floating OSW Resource in Barbados

The wind resource for floating OSW largely matches that for fixed OSW (as discussed at Section 2.3.2 and in Figure

2.8). It is worth noting that projects utilising floating technology in deeper water are likely to benefit from a minor increase in mean wind speed compared with fixed turbines if located further from shore.

Looking at suitable sea depths for floating OSW in Barbados (Figure 3.14) it can be seen that the available area for conventional floating (60-200m depth) is less than that for deep floating (200-1000m). This is intuitive due to the wider depth range for deep floating OSW. Due to the local seabed bathymetry there is a high degree of variability in water depth in the sea space surrounding the island but there are some areas of depth suitable for conventional fixed floating wind technology at reasonable proximity to land – primarily located to the south of the island.

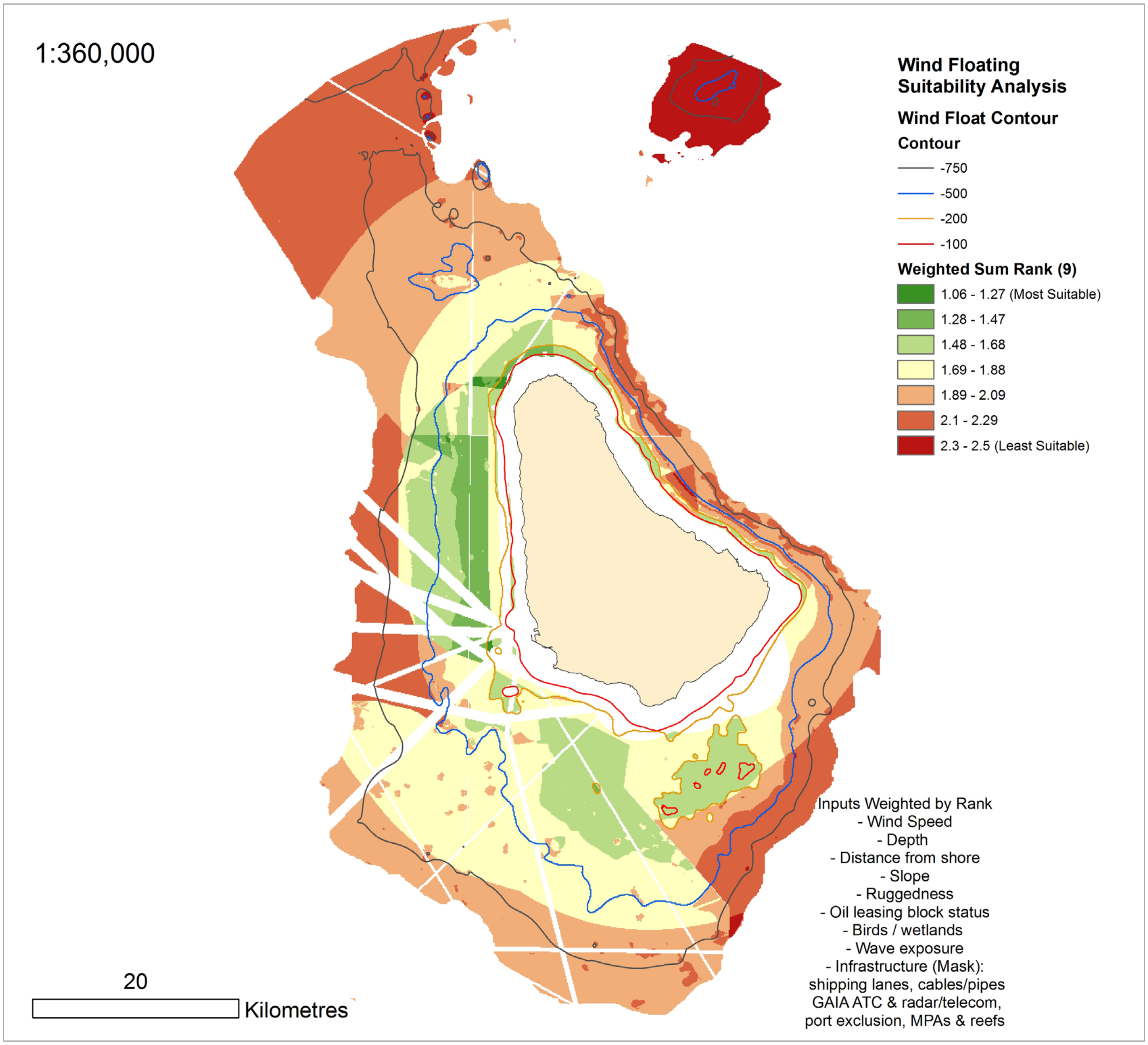
Figure 3.14 Barbados: areas with suitable sea depth for floating OSW



3.4 / FLOATING OSW – LOCATIONAL GUIDANCE

Figure 3.15 below presents the results of detailed locational guidance analysis with respect to floating OSW undertaken with use of GIS software.

***Figure 3.15** Floating OSW - Weighted sum suitability analysis map*



The Locational Guidance exercise for floating OSW identified a number of very large areas potentially suitable for deployment of the technology within a short to medium distance to shore (approximately 3km – 20km). These areas are distributed to the south, west and off the north coast of the island with each area being of sufficient size to host a project of substantial scale. The best scoring area is on the west coast, which benefits from a more sheltered wave regime, but areas to the north and south also score highly. The excluded areas due to the presence of major shipping routes and subsea infrastructure are notable in the south west around Bridgetown.

It should be noted that the analysis applied a significant weighting on distance to shore, preferring sites located closer to land. This weighting was applied to take account of the CAPEX and OPEX benefits of locating projects closer to shore. It may be prudent in any future exercise to relax this weighting or employ another methodology to select an additional area of interest located further from shore, particularly given the more recent industry trend of projects under development increasing in size and moving farther from shore. While such an area may result in a higher projected cost of energy this may be offset by a significant reduction or complete elimination of visual impact concerns.

While a number of key environmental and sea use datasets were included in the Locational Guidance work further work remains to more fully capture other stakeholder groups such as commercial and recreational fishers, recreational users of the sea including boating and windsports, and others. These considerations are intended to be taken further into account in the suite of studies to be carried out in Barbados during 2020.

3.5 / FLOATING OSW - DISCUSSION

In terms of commercial readiness, whilst there are several operational floating wind demonstration projects (five in Europe and three in Asia), including one array project, these have required substantial financial assistance in the form of grants and often revenue support to be realised. Floating technology therefore currently presents a higher cost, and greater degree of commercial uncertainty, than fixed OSW. That said, the projected pipeline of international projects predicts an explosion of activity in the next five years. This can be interpreted as an acceptance of the technological risk by the developer community and an indication of the increasing maturity of the sector.

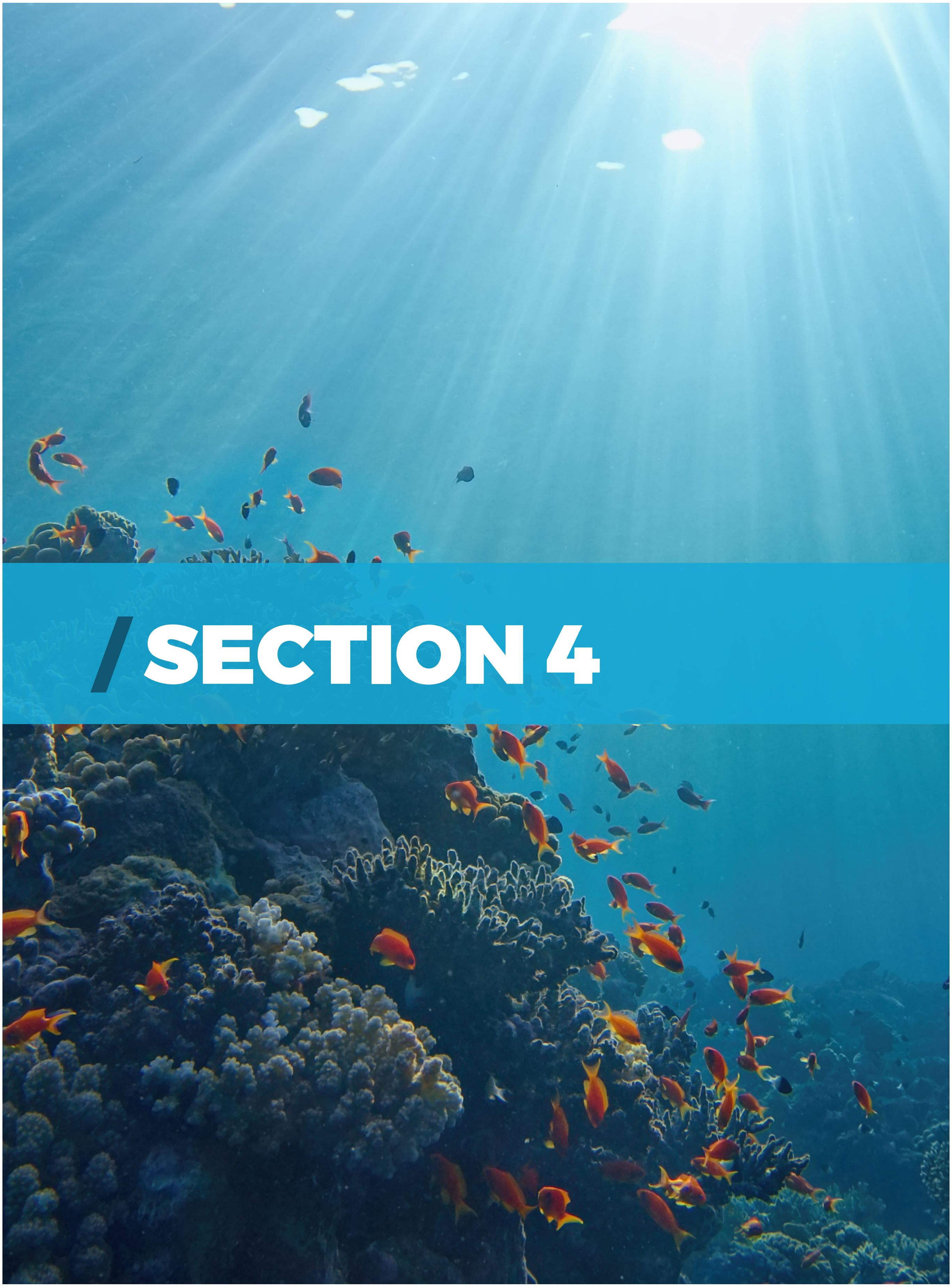
While current average LCOE levels are relatively high at $0.17 USD/kWh (in the region of 50% higher than fixed OSW) LCOE is projected to reduce significantly in the near to medium term. As with fixed OSW, this cost reduction is largely driven by and linked to economies of scale and the ready availability of an advanced and highly competitive supply chain. Again, considering the relatively low overall level of electricity demand in Barbados, it will be challenging in the near to medium term to deliver the scale required to achieve LCOE levels seen in larger markets elsewhere. However, the consistently high price of electricity seen in Barbados and other similar island settings may boost commercial viability and lead to acceptance of the technology at LCOE levels that are higher than those expected in other larger markets.

Floating OSW is a highly attractive proposition in Barbados both from a wind resource and depth perspective. As with fixed OSW, preliminary assessment suggests that the quality of the wind resource in the country is for the most part, 'attractive'. The availability of suitable sea depth for conventional and deep floating OSW relatively close to land is far more favourable for floating than fixed wind technology. It should be noted that investigation of additional geotechnical factors such as ruggedness and substrate type is beyond the scope of this report and these factors may restrict suitability within the broader area of interest – although floating OSW is less sensitive in this regard than fixed OSW.

As discussed above, due to the positive weighting applied to distance to shore criteria, the Locational Guidance exercise highlighted areas of interest that are located within a short to medium distance from land. While locating projects in the nearshore area will provide CAPEX and operational cost benefits, the turbines themselves will be visible from shore. This may be less of an issue for a project located off the north coast of Barbados when compared with projects located off the more heavily populated and touristed west and south coasts. It may be prudent to consider project locations further from shore where the turbines would only be partially visible or not visible at all. As a general guide, and dependent on the height of turbine deployed, this location would need to be a minimum of 35km from shore to ensure partial visibility and 50km or more from shore to ensure that it is not visible to observers at sea level onshore. Investigation of such an area was not included in the previous round of Locational Guidance but improvements in wind data availability now make this possible for any further iterations of this work. Pursuing larger scale project development may provide a route to reducing or offsetting the increased costs incurred in developing any project further offshore. Carrying out a robust tourism impact study – as is planned to be carried out during 2020 - will be an important step in determining a potential route forward. The analysis undertaken is also limited by availability of data in terms of consideration of other sea users and so, in determining preferred development locations, it will be necessary to consult widely so as to minimise conflict with other users of the sea as far as possible. Such work could complement and form part of wider marine or blue economy spatial planning exercises.

In conclusion, floating OSW appears to be a very suitable technology option for Barbados based on a number of technical and resource considerations. The technology is not excessively limited by sea depth constraints and Locational Guidance work has concluded that there are a number of options for siting of projects off all coasts except the east of the island. Indeed, the naturally steep bathymetry down to deep waters close to shore makes Barbados generally very attractive for floating OSW deployment. As a result, projects utilising floating rather than fixed wind technology will be much less constrained in terms of where they can be deployed and overall scale of project.

Possible additional benefits of floating OSW include compatibility with smaller scale port infrastructure, possible reduced requirements in terms of supply chain capability, and reduced visual impact with turbines located further from shore than fixed OSW. Whilst initial Locational Guidance work has proven useful in identifying potential areas for development, it is recommended that further consideration is given to identifying an additional location or locations further from shore. This will enable a technical and cost comparison with areas identified closer to shore.



/ SECTION 4

/ OCEAN THERMAL ENERGY CONVERSION (OTEC)

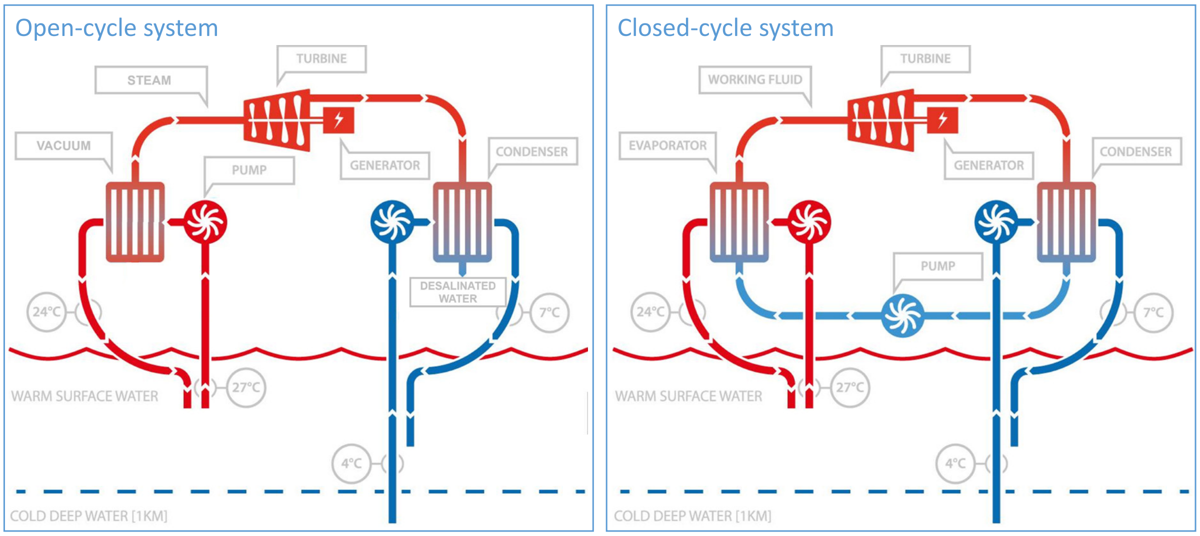
4.1 / OTEC - OPERATING PRINCIPLE

OTEC utilises the difference in temperature between surface and deep water layers of the ocean. This difference in temperature is created by solar energy stored as heat in the upper layers of the ocean and is therefore generally greatest in warmer tropical regions. OTEC technologies pump warm water from the surface layer and cold water from the deep ocean (generally around 1000m deep) to a generation plant which can be located either onshore or on an offshore platform. Electricity generation is achieved via an open-cycle system, a closed-cycle system or a hybrid system. The operating principles of each are;

- In an open-cycle system warm seawater is vaporised in a vacuum (to create steam) which drives a turbine and is condensed on the other side of the turbine using cold seawater. A useful by-product of this system is that the water exiting the turbine is desalinated.
- A closed-cycle system operates in a similar manner except that instead of seawater flowing through the system, a working fluid with a low boiling point (such as ammonia) is used with hot and cold seawater used to evaporate and condense the working fluid which is recycled in the closed-cycle.
- In a hybrid system warm seawater is turned into steam in a vacuum chamber (just as in an open-cycle system), but the resulting steam is used to vaporise a working fluid in a closed-cycle system which drives a turbine. The rational for the hybrid system is that the perceived technical benefits of the closed-cycle system can be had whilst at the same time also generating desalinated water as a useful by-product.

A schematic diagram of an open-cycle and closed-cycle system are provided in Figure 4.16.

***Figure 4.16** Open-cycle and closed-cycle OTEC systems*



Source: Adapted from Bluerise (2016).

Figure 4.17 shows what an OTEC project may look like in practice. It illustrates a 10MW offshore closed-loop project with a barge moored in deep water hosting heat exchangers, pumps and a generator, pipes suspended underneath down to 1000m, and a subsea cable transmitting the electricity generated back to shore.

***Figure 4.17** Illustration of a 10MW floating closed-loop OTEC project*

Source: Naval Group (2014)

OTEC technology, in contrast to intermittent or variable renewable energy technologies, has the potential to produce baseload (steady) electricity generation at a high capacity factor (up to 90%). The system can also theoretically be configured to derive added value from ancillary activities such as:

- Potential production of fresh water (in open loop or hybrid systems)
- Use of waste cold sea water to run sea water air conditioning (SWAC) plant (see Section 5)
- Use of waste cold sea water to run underground pipes in soil for chilled-soil agriculture
- Use of waste cold sea water (which is nutrient rich) for aquaculture

4.2 / OTEC - DEVELOPMENT STATUS

The OTEC sector can be described as being in a pre-commercial phase where a significant amount of technology R&D activity is underway and a small number of individual single scale prototypes have been installed over several decades and operated over a limited time. Single scale prototypes have often doubled as Seawater Air Conditioning (SWAC) prototypes. Developmental work is now underway on a handful of industry-leading commercial projects however, only a very small number of these are expected to be operational by 2025 and there appears to be a trend of proposed projects stalling.

In terms of the historical development of the sector, the first operational OTEC projects were installed in the 1970s with a resurgence in technology and project development since the beginning of the 2000s. Projects have tended to focus on attempting to address power generation, cooling and seawater desalination issues for islands in tropical regions. Selected projects installed to date include:

- **Japan, Imari** - 30kW multi-use plant operational from 2003.
- **Japan, Okinawa** - 50kW plant completed in 2013.
- **United States, Hawaii** - 103kW closed cycle system at the Natural Energy Laboratory in Hawaii in 1979.
- **United States, Hawaii** - 1MW open cycle plant operated in Hawaii between 1993 and 1998.
- **South Korea, Busan** - 1MW capacity floating barge unit installed and tested in Korea for a few days in September 2019 with 370kW gross power achieved before conclusion. The system will next be transported to Kiribati for installation.

A small number of commercial projects are now in development. These 'pathfinder' projects will be absolutely critical in demonstrating that OTEC technology can deliver on its technical promise and pave the way for large scale project replication. Due to the nascent nature of the OTEC industry there are no suitable industry reports or market analysis data sets available for analysis. As such the IDB previously commissioned industry engagement via questionnaire to gain a complete picture of the industry. This work has been more recently complemented by further industry engagement and desk-based research to garner the latest information. Responses to industry consultation were provided in confidence and as such cannot be published however some interesting, more generic points arising from the exercise are outlined below:

- The information gathering exercise revealed the various OTEC developers, in general, in a positive light.
- Comparing the analysis carried out in 2017 with the more recent update work there does however appear to be a trend of proposed projects stalling. No significant progression can be seen on many of the projects in development.
- The largest capacity project built to date is the 1MW open cycle plant operated in Hawaii from 1993 to 1998. The largest currently operational plant is also in Hawaii and is rated at 103kW. The recent short test of a 1MW floating barge OTEC plant in South Korea by KRISO is however notable and the success or otherwise of its proposed installation in Kiribati could be a critical determinant in how the industry progresses.
- Despite challenges in getting large scale projects financed, an early-stage global project pipeline does exist with feasibility assessments having been conducted for a number of tropical island locations.
- All projects built to date have been onshore except for the recent test in Korea.
- All technology developers which responded to the consultation are focused on closed-loop OTEC technology due to the increased efficiencies that this variant offers. A pure closed-loop system limits the potential for production of fresh water as a by-product of the process to running desalinisation plant with the electricity generated. Plants located offshore, whilst looked upon favourably on in terms of reducing the LCOE, create logistical limitations in terms of delivering ancillary benefits such as production of fresh water and SWAC potential.
- Technology developers seem to have largely converged on offshore OTEC plants for future commercial projects due to cost savings achievable although this does limit the availability of hot or cold water for secondary use (such as SWAC) onshore. However a trend can be seen whereby developers are now expressing an openness to onshore projects where added value from ancillary benefits can be more readily achieved.
- All technology developers have indicated an intention to focus on developing projects ranging from 0.5-10MW net power. It seems that this level of output needs to be proved before moving to larger projects.
- Technology development focus in general seems to have been concentrated on heat exchanger and large-scale pumping plant. Less attention seems to have been paid by many of the developers to the installation, anchoring and operation and maintenance of the piping infrastructure although some companies do specialise in this aspect.
- OTEC plants use electricity to run the pumps that drive the process. This leads to a parasitic load of about one third of the electricity generated. Some developers referred to nameplate capacity of projects based on gross rather than net generation. The quoted achievable capacity factor of 90% refers to the net generation figure.

Looking in more detail at the economics of OTEC technology, there is a predictable paucity of information due to the low number of projects constructed. Studies which have been undertaken also show wide ranges in terms of cost estimates. IRENA (2014) compiles available info to show that estimated capital costs for existing projects and planned projects under 10MW range between about $16 and $32 million USD per MW. With scale, increased global installed capacity, and a sharp learning curve, it is predicted that costs could however come down to as low as $2.5 million USD per MW by the time 100MW is installed globally. There is therefore a route to delivery of acceptable LCOE from this technology, but it is highly likely that the next phase of projects, if and when built, will have LCOE figures well over current market levels in Barbados. Therefore, a combination of risk-accepting capital and innovative funding mechanisms will be required to fund any first pathfinder projects.

4.3 / OTEC – OPERATIONAL REQUIREMENTS

4.3.1 Operational requirements

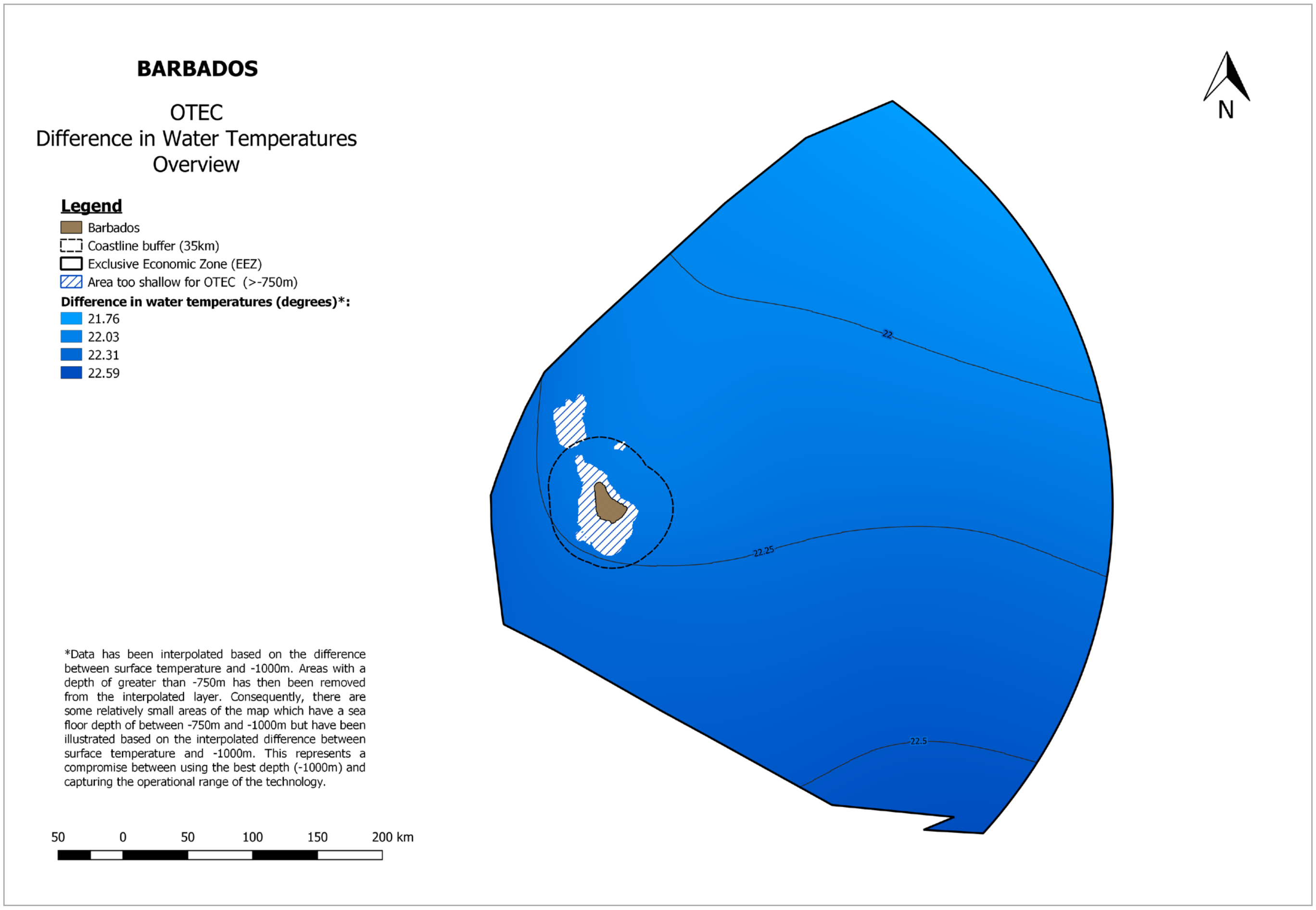
Industry experts contacted during the consultation exercise advised that a temperature differential between sea surface and deep-sea water of 20 degrees centigrade would be required for an OTEC project, with greater temperature differentials likely to yield additional efficiencies. This translates to a basic requirement for sea surface temperatures of around 25 degrees and water depth of 1000m (where water temperature will generally be around 5 degrees) so in practical terms OTEC is only suited to tropical regions.

Bathymetry is also a key factor for OTEC projects with the need to access deep cold water as close to shore as possible. Industry consultation suggests that reaching 1000m depth within 10km of shore is desirable for project economics, although there is no technical reason why it wouldn't be possible to operate an OTEC plant at much greater distances from shore. In the case of Barbados, 1000m depth is reachable within approximately 5km - 10km on the east coast of the island and within approximately 20km - 30km off the west coast.

4.3.2 Resource in Barbados

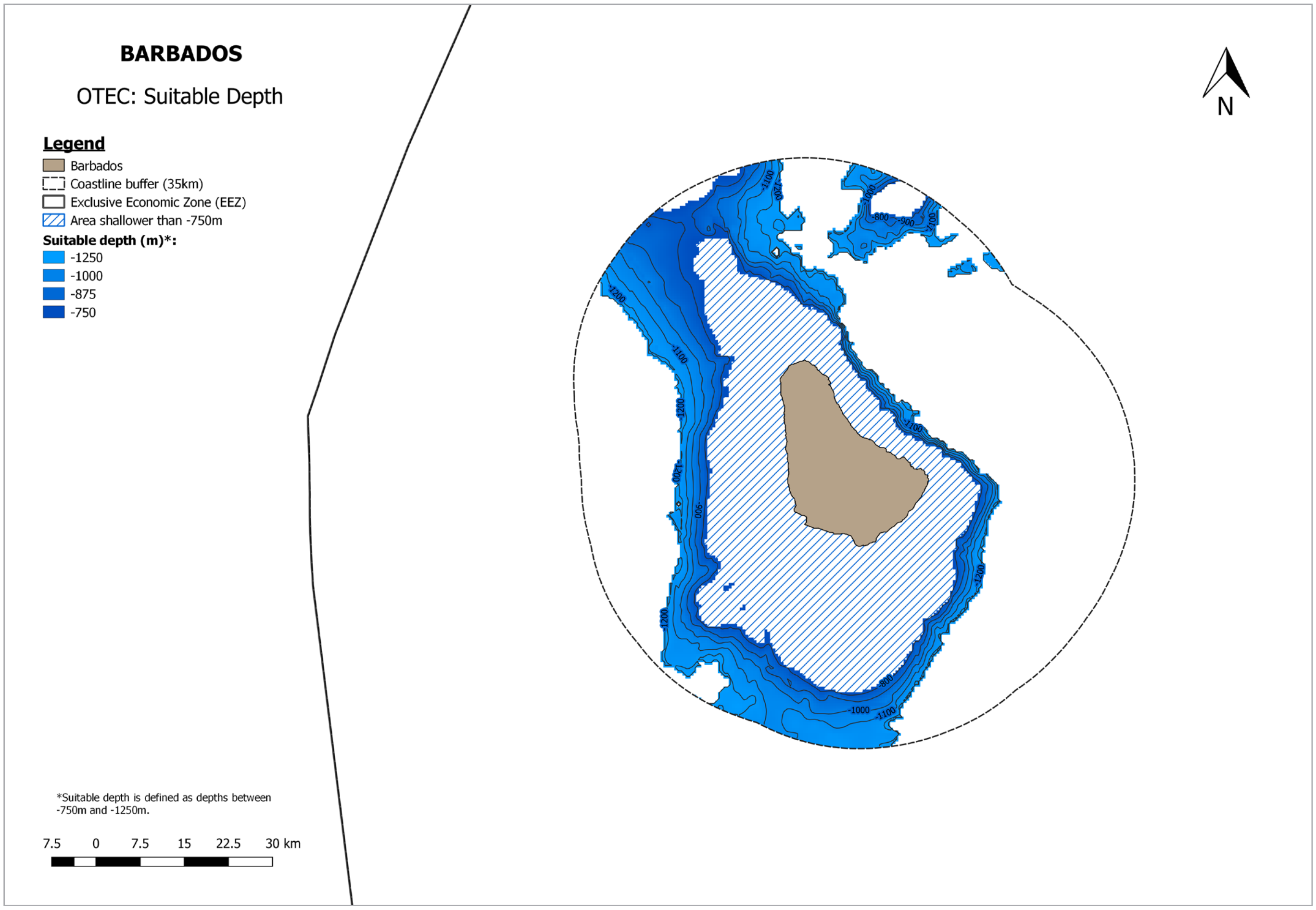
OTEC requires an overall temperature differential between sea surface and working water depth of about 20 degrees centigrade. This has been explored for Barbados in Figure 4.18 using interpolated data from the World Ocean Atlas (2018) which compares average ocean surface temperatures with the average temperature at 1000m depth. This data shows that there is acceptable temperature differential and suitability for OTEC throughout the EEZ, with slightly higher temperature differential to the southwest.

Figure 4.18 Resource potential for OTEC in Barbados



A depth of 1000m is generally sought for in locating OTEC plants and a range of between 750m and 1250m is considered appropriate for identifying candidate areas. Such areas are illustrated out to 35km from shore in Figure 4.19 below. In practical terms, developers would look for locations with suitable depth and temperature as close to shore as practical and within close range of a substantive electrical grid connection or demand centre and port facilities for operations and maintenance. As can be seen in Figure 4.19, there are substantial areas of suitable depth located within a reasonable distance from land on both the east and west coasts of the island.

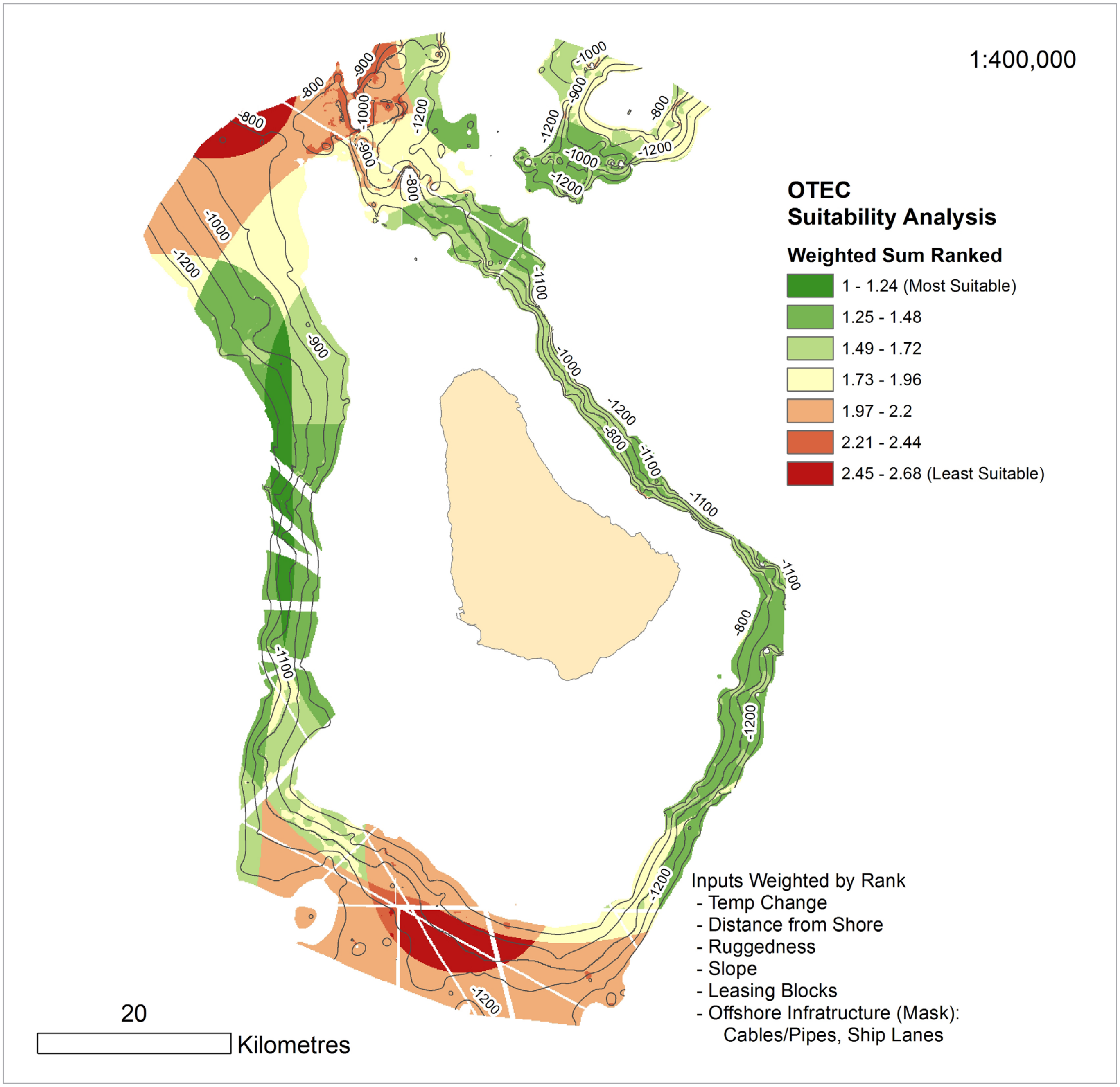
Figure 4.19 Barbados: areas with suitable sea depth for OTEC (or SWAC)



4.4 / OTEC – LOCATIONAL GUIDANCE

Figure 4.20 below presents the results of detailed locational guidance analysis with respect to floating offshore OTEC undertaken with use of GIS software.

Figure 4.20 OTEC - Weighted sum suitability analysis map



The Locational Guidance exercise for floating offshore OTEC plant identified a wide range of large areas of sea space potentially suitable for deployment of the technology. The identified areas vary in that some are very close to shore on the more wave exposed and less developed east coast and others are further offshore, but still within reasonable distance to landfall, on the west coast.

Potential project locations on the west side of the island may prove to be more attractive to developers given the reduced wave exposure due to the shadowing effect of the island from the prevailing swell direction. An additional consideration is the presence and relative strength of the electrical infrastructure on the west versus east coast.

Visual impact is not considered to be in any way significant as floating plant will strongly resemble a boat or ship; and due to its low profile will only be visible within a short distance. As with floating OSW, although a number of key environmental and sea use datasets were included in the Locational Guidance work, further work remains to more fully capture other stakeholder groups and sea users.

4.5 / OTEC - DISCUSSION

OTEC technology presents an attractive proposition in Barbados and the Caribbean region in general because of the excellent thermal resource, access to deep waters in close proximity to shore, and the potential to generate a steady baseload of electricity alongside other ancillary activities such as SWAC, desalination, aquaculture, and chilled soil agriculture. Nonetheless, technology risk is a significant issue due to the limited track record of the sector and small number of operational plants installed globally. The presence of medium to large maritime construction companies in the sector could provide a means to manage this risk through provision of warrantees and guarantees.

Significant research and consideration would be required in determining the optimal location and scale of such projects. The design of project to be pursued will be important in determining the range of ancillary benefits achievable. Market players seem to be focussed on closed-loop offshore plants. With a closed-loop design fresh water production is not a natural by-product (but can be produced with the electricity generated), and with offshore plants SWAC and fresh water production are logistically challenging.

Achieving an acceptable cost of energy is likely to be an issue for the next generation of demonstrator projects. It is however essential for this next generation to be built somewhere in order for future installations to benefit from the learning and reduced LCOE. To make projects viable it may be necessary to attract significant grant funding and some developers noted that it may be necessary for upcoming projects to be situated onshore to enable added value through ancillary benefits to deliver an acceptable financial outcome and LCOE.

Additionally, while a number of the elements of an offshore OTEC plant (such as anchors, pipelines, heat exchangers) have been deployed as part of projects, in other offshore sectors significant gaps remain in the understanding of the likely environmental impacts – both positive and negative - of a large scale OTEC plant. Some key questions include; the impact of continuous mixing of surface and nutrient rich deep water layers, potential impacts on deep water species, organism attraction and biofouling, noise pollution, and others. These questions will remain largely unanswered until a track record has been established through the operation of the first pilot projects offshore.

SECTION 5

/ SEA WATER AIR CONDITIONING (SWAC)

5.1 / SWAC - OPERATING PRINCIPLE

SWAC systems utilise thermal energy contained in bodies of water such as rivers, lakes and oceans to provide energy efficient heating or cooling. In cold climates the relative warmth of nearby water can be harnessed in a heat pump whereas in warm regions with cooling demand cool waters are used in the same way. The commercial proposition is that rather than using electricity to cool (or heat) the refrigerant in air conditioning systems, a comparatively lower amount of electricity can be used in pumping water around the system, leading to financial savings through improved energy efficiency and associated energy savings. SWAC systems are therefore generally well suited to consumers situated close to shore with large heating or cooling demand.

From the perspective of application of the technology in Barbados, SWAC systems would seek to utilise cold seawater from the deep ocean in a heat exchanger onshore to directly cool fresh water (or another working fluid) which could be used in traditional air-conditioning systems in buildings or district cooling systems. In doing so SWAC offers the potential for year-round supply of cost effective cooling. The technology can also be complementary to OTEC in that the waste cold seawater from an OTEC cycle can be used in SWAC systems.

5.2 / SWAC - DEVELOPMENT STATUS

SWAC can be considered to be in a pre-commercial phase where a significant amount of technology R&D activity has been undertaken, and a small number of individual projects have been deployed globally over a number of years. When heating as well as cooling projects are included in a global project count it can be said that there is a substantial base of projects installed and operational. There is however substantial variety in the operational projects, with many tapping in to close-to-surface water for heating or cooling purposes, some utilising deep lake water, and others using deep sea water. Generally projects using surface fresh water would be viewed as more straightforward due to the lack of the need for deep water pipelines and corrosion protection from salt-water.

A typical SWAC project in Barbados, whilst using the same core technologies and principles, would be viewed as more complex due to the requirement to pump seawater from significant depth (~1000m) and considerations around ocean exposure and wave action. Existing projects are also not homogenous because of the specific resource conditions and cooling or heating demands of the host location. These differences in technical complexity, resource, and demand mean that viability must be carefully assessed on a project by project basis. In the context of Barbados and the wider Caribbean, with high energy prices and consistent year-round demand for cooling, SWAC could be deemed to be in general closer to commercial readiness than elsewhere, notwithstanding technological considerations.

There are a small number of operational SWAC projects located on islands in tropical regions typically serving larger tourism centres such as hotels. There are also other larger projects said to be in the advanced development stage. Information on larger public utility type projects is generally freely available online or presented at conferences; however, detailed information on private projects is limited.

Selected SWAC projects installed on islands to date include but may not be limited to:

- **French Polynesia, Bora Bora** - SWAC system installed in the InterContinental Hotel in 2006. Limited public information available.
- **French Polynesia, Tetiaroa Atoll** - SWAC system installed at the Brando Resort. No further information available.
- **Hong Kong** - SWAC systems operational at the Excelsior Hotel and Hong Kong Shanghai Banking Corporation Office. Limited public information available.
- **United States, Hawaii** - Three projects in operation. Natural Energy Laboratory of Hawaii (NELHA) SWAC installed in 1987, and later upgraded. Two smaller projects at the University of Hawaii, and also Kahala Resort. A large-scale district cooling project has been mooted for development in Honolulu for a number of years; however, research indicates that this has not reached financial close or been developed further.
- **Other** - Additional SWAC projects have been promoted and developed to varying degrees in Aruba, Mauritius, and Curacao but at the time of writing are not known to be operational.

Selected other SWAC projects installed to date include:

- **Canada, Toronto** - Deep Lake system for district air conditioning. Installed in 2003.
- **Canada, Halifax** - Seawater cooling system completed at Purdy's Wharf in 1989 providing cooling to a large office block.
- **Finland, Hamina** - Google data centre cooled by seawater. Operational since 2011.
- **Netherlands, Amsterdam** - District cooling utilising nearby deep water lakes installed in 2006.
- **Sweden, Stockholm** - Industry leading project in Stockholm operational since 1995 as well as various other projects in other cities in Sweden.
- **United States, New York** - Lake Source Cooling project for cooling of Cornell University campus buildings. Installed in 2000.

5.3 / SWAC – OPERATIONAL REQUIREMENTS AND RESOURCE IN BARBADOS

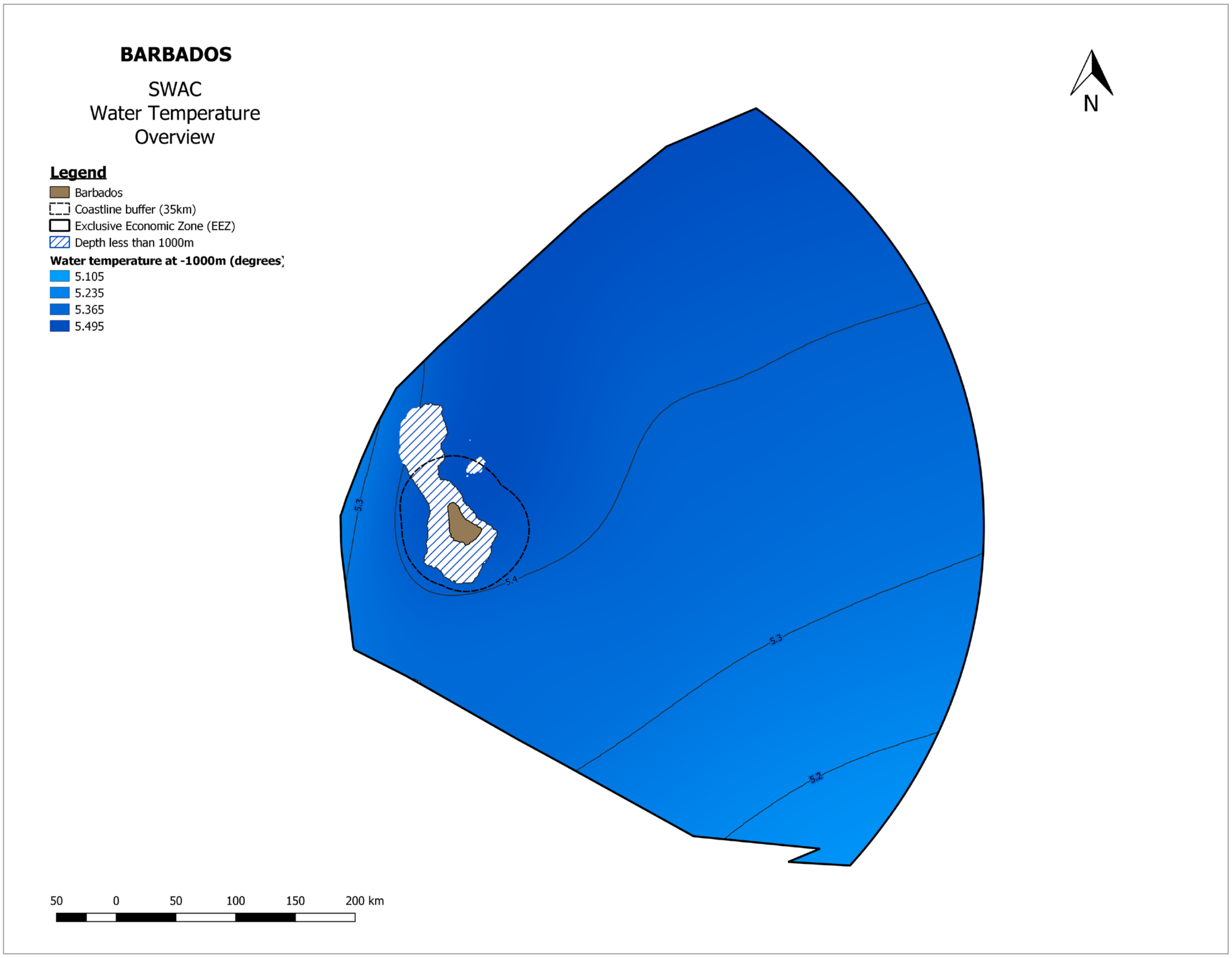
5.3.1 Operational requirements

Specific operational requirements for SWAC are highly site specific related to a number of technical and financial considerations such as level and nature of cooling demand, proximity to deep water, water column temperature profile, shoreline conditions, local energy pricing etc. Some generalisations can however be made that viable SWAC cooling projects must access cool deep water (5-8 degrees centigrade) at minimal distance from shore and as close to possible to a significant and preferably year-round cooling demand in a market where the price of electricity is relatively high.

5.3.2 Resource in Barbados

The temperature of seawater at depth, distance from shore to deep water, and availability of load are the key resource requirements for SWAC projects. In terms of temperature, consultation with industry experts suggests that water depths of around 1000m would be required as close to shore as possible for a viable project. Suitable sea depths are therefore almost identical to OTEC (with Figure 4.19 in Section 4.3.2 showing water depths between 750m and 1250m in Barbados). Industry also suggests that a temperature of 5-8 degrees would need to be available at this depth for a viable SWAC project. Figure 5.21 uses World Ocean Atlas (2018) data to show sea temperature at 1000m depth in the Barbados EEZ. This shows acceptable water temperatures for SWAC projects throughout, with slightly lower temperatures found in waters to the south and east of the EEZ.

Figure 5.21 Resource potential for SWAC in Barbados



5.4 / SWAC – LOCATIONAL GUIDANCE

No specific weighted sum suitability analysis was undertaken for SWAC; however, analysis of the OTEC resource and suitable depths in the country can be relied upon to provide a useful indication of potential. OTEC analysis demonstrates that there are cool deep waters in close proximity to the shore on the east coast and slightly further from shore on the west coast. As discussed previously in this report, demand for cooling is known to be limited on the less developed east coast. There are numerous heavy users of cooling load (notably hotels) for which a SWAC project could be suitable on the west coast. The south coast may also offer some potential although the distance to suitable deep water is slightly greater than the west coast which may adversely affect project economics.

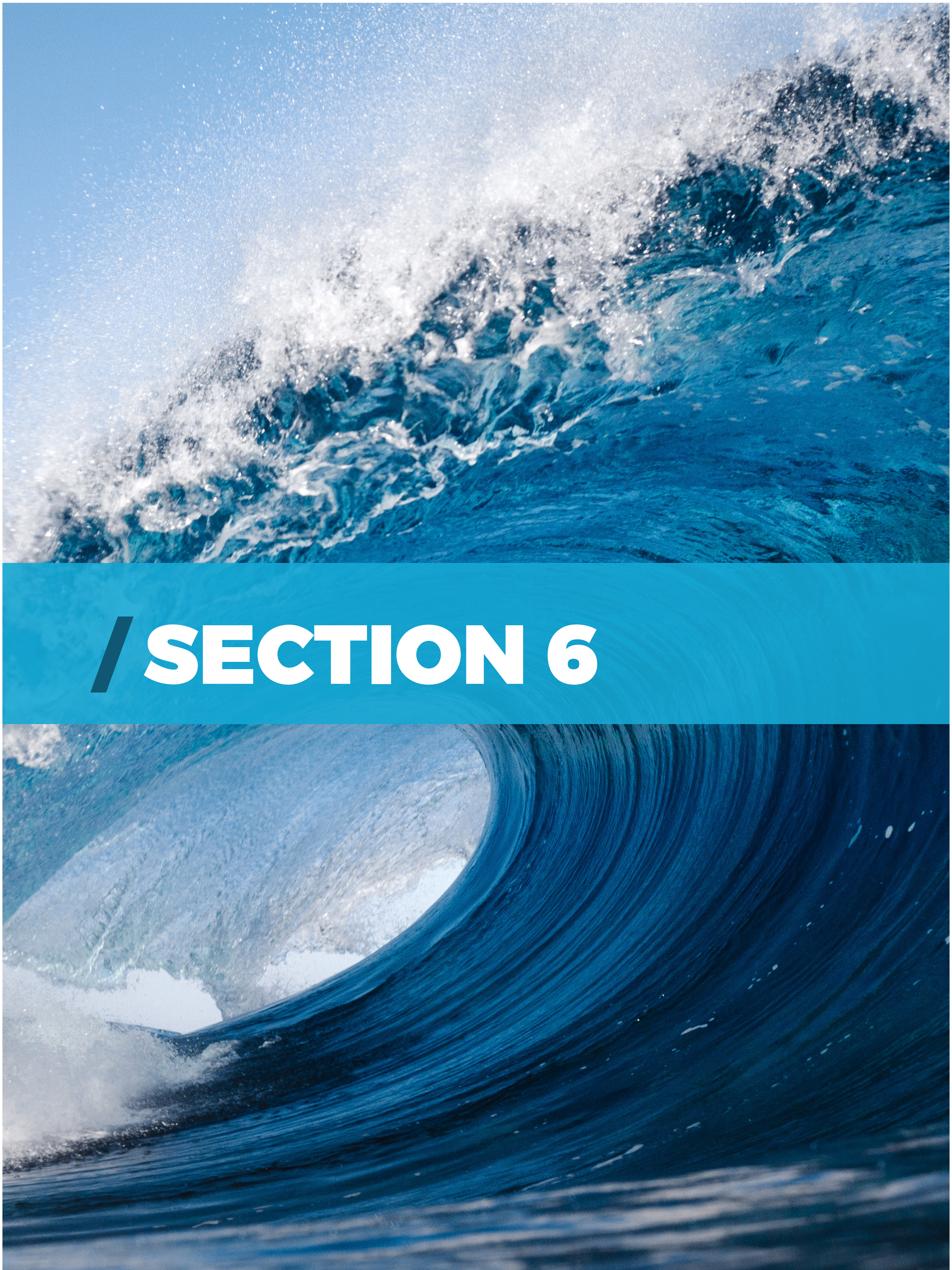
5.5 / SWAC - DISCUSSION

Based on the results of the analysis conducted for OTEC, SWAC can also be considered to be an attractive technology for Barbados. However it is considered that, due to its highly site specific nature, the potential for its implementation is on a significantly smaller scale than the other offshore renewable energy technologies discussed in this report.

In terms of technology readiness, whilst the base of operational SWAC projects is limited, the technology is simpler than OTEC and, other than potential complexities around pipelines, should be relatively straightforward to implement. Examples of potential pipeline considerations include the need for enhanced engineering design to deal with wave action such as armouring of pipelines or a requirement to protect pipelines altogether through onshore directional drilling. These engineering solutions do not prohibit development, but rather need to be factored in at the design stage and can therefore be considered as part of an assessment of overall project viability.

Market fit would seem to be good given that energy prices in Barbados are high and, as with many other tropical island locations, cooling accounts for a significant proportion of energy usage across all sectors. It therefore seems likely that numerous suitable locations for SWAC projects could exist in Barbados, but further work to identify optimal locations is beyond the scope of this report. The potential for SWAC to deliver baseload cooling supply is also a relevant consideration which boosts the importance of the technology in the context of Barbados when the technology is compared against intermittent or variable renewable energy technologies such as solar photovoltaics or wind.

Identification of suitable customers for cooling load (such as a new or existing industrial, commercial or hospitality sector users) with close nearshore access to deep cool waters would seem to be a logical next step and pre-requisite for progression of a SWAC project in Barbados. It is also worth noting that a SWAC project or projects may be suitable for consideration as a lower risk 'stepping stone' to a larger onshore OTEC project and need not be considered on a standalone basis.



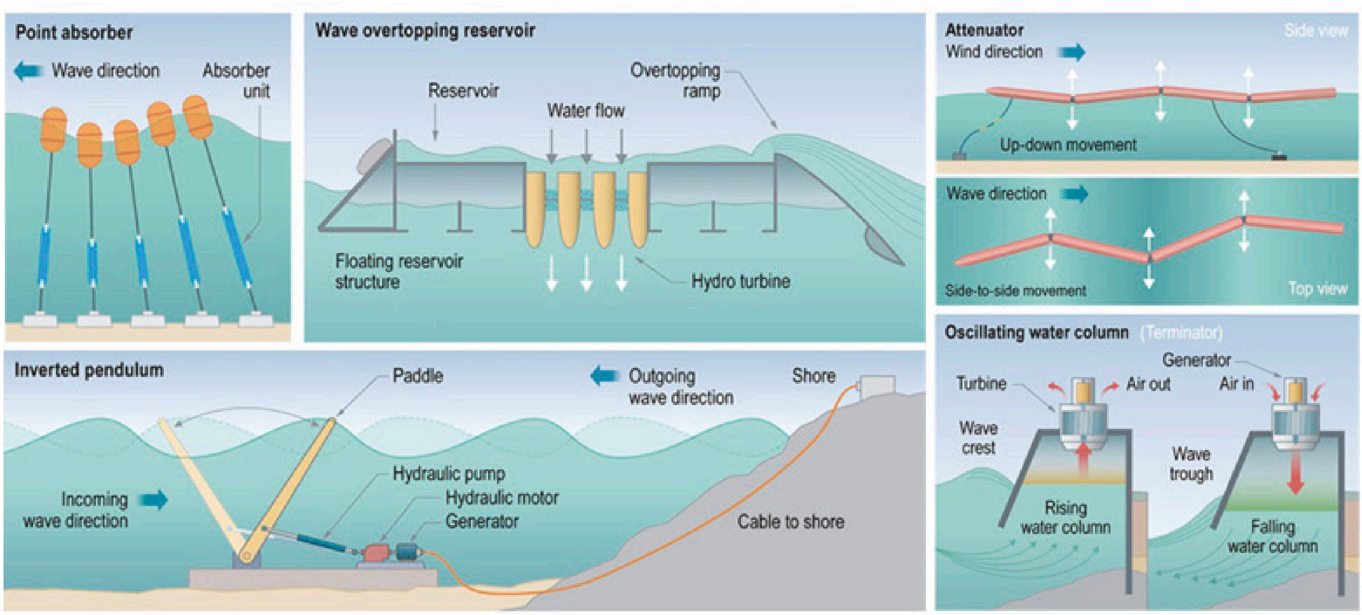
/ SECTION 6

/ WAVE ENERGY CONVERSION

6.1 / WAVE - OPERATING PRINCIPLE

Waves are created by the action of the wind on the surface of the oceans. Wave energy conversion involves utilising the movement of waves to drive an electric generator. There are numerous and highly varied concepts under development, some of which are outlined in Figure 6.22. The majority of concepts convert the movement of waves into mechanical movement of the device or device parts, with that movement then used to drive an electrical turbine. Other concepts use the movement to pump water to shore and drive a hydro turbine, or use the waves to fill a reservoir for a very low head hydro turbine. Many pumping concepts have the potential to integrate energy production with provision of desalinated water by utilising accumulated pressure to drive a reverse osmosis process. Depending on the wave climate in which they are deployed, wave energy technologies offer the potential for relatively consistent energy capture which can overlap and potentially complement other sources of renewable generation – in particular wind energy.

***Figure 6.22** Examples of wave energy device types*



Source: US DOE (2015)

6.2 / WAVE - DEVELOPMENT STATUS

The Wave Energy sector can be described as being in a prototype demonstration development phase with no real commercial application of the technology to date. A number of full-scale prototypes have been installed in open ocean conditions with various degrees of success; however, the first fully commercial array projects have yet to be deployed. A handful of high-profile industry-leading companies, such as Pelamis Wave Power and Aquamarine Power have previously entered receivership; however, there are many other competing concepts still being actively developed. The European Marine Energy Centre (EMEC) maintains a register of companies actively developing wave energy concepts. The number of companies on this register currently stands at 244 (EMEC, 2019).

Selected projects of significant scale installed to date by companies which are still active in the sector include:

- **Australia –** Carnegie Wave Energy, CETO. Three 250kW units installed in Western Australia in 2015. Array produced power for a Navy Base and also contributed towards a desalination process on site.
- **Finland / United Kingdom –** Wello Oy, Penguin. 500kW iteration of technology tested at EMEC from 2011. The same device was refitted and was installed at EMEC through 2017 and 2018. The company has manufactured, and will soon test an updated 1MW version of this device at EMEC in an array in 2020.
- **Norway / United States –** Fred. Olsen, BOLT. The 50kW BOLT Lifesaver was originally tested in Falmouth, England and was refitted and redeployed in Hawaii in 2016. In 2019, the device was installed again and was reported to be operational for 100 days with 100% uptime.
- **United States –** Ocean Power Technology (OPT), PowerBuoy. OPT has tested its PowerBuoy technology in a variety of locations and conditions. Previously deployed at 150kW scale in Scotland in 2011, and deployed at 15kW scale for a US Navy project in New Jersey, USA in 2017. Most recently, the company installed a device off Italy in a project linked to battery storage for charging autonomous underwater vehicles.
- **Australia / UK –** Bombora Wave Power are developing a technology for shallow depths which can be deployed 'standalone' or potentially incorporated into new breakwater structures. First in-ocean trials were held in 2017 with a 1.5MW EU supported demonstrator project currently under construction in Wales.

6.3 / WAVE – OPERATIONAL REQUIREMENTS AND RESOURCE IN BARBADOS

6.3.1 Operational requirements

With such a nascent industry and so many varied technology concepts under development it is not possible to accurately specify operational requirements for wave energy devices. That said, cost considerations mean that developers generally prefer sites close to shore and shoreside operations bases and port facilities, in water of generally 10m to 100m depth. Some developers also actively look to install on breakwaters or piers. The required wave resource varies by technology. Different concepts are designed to operate within a given range of wave heights and periods – although some scope exists to optimise or 'tune' individual concepts to a particular wave climate.

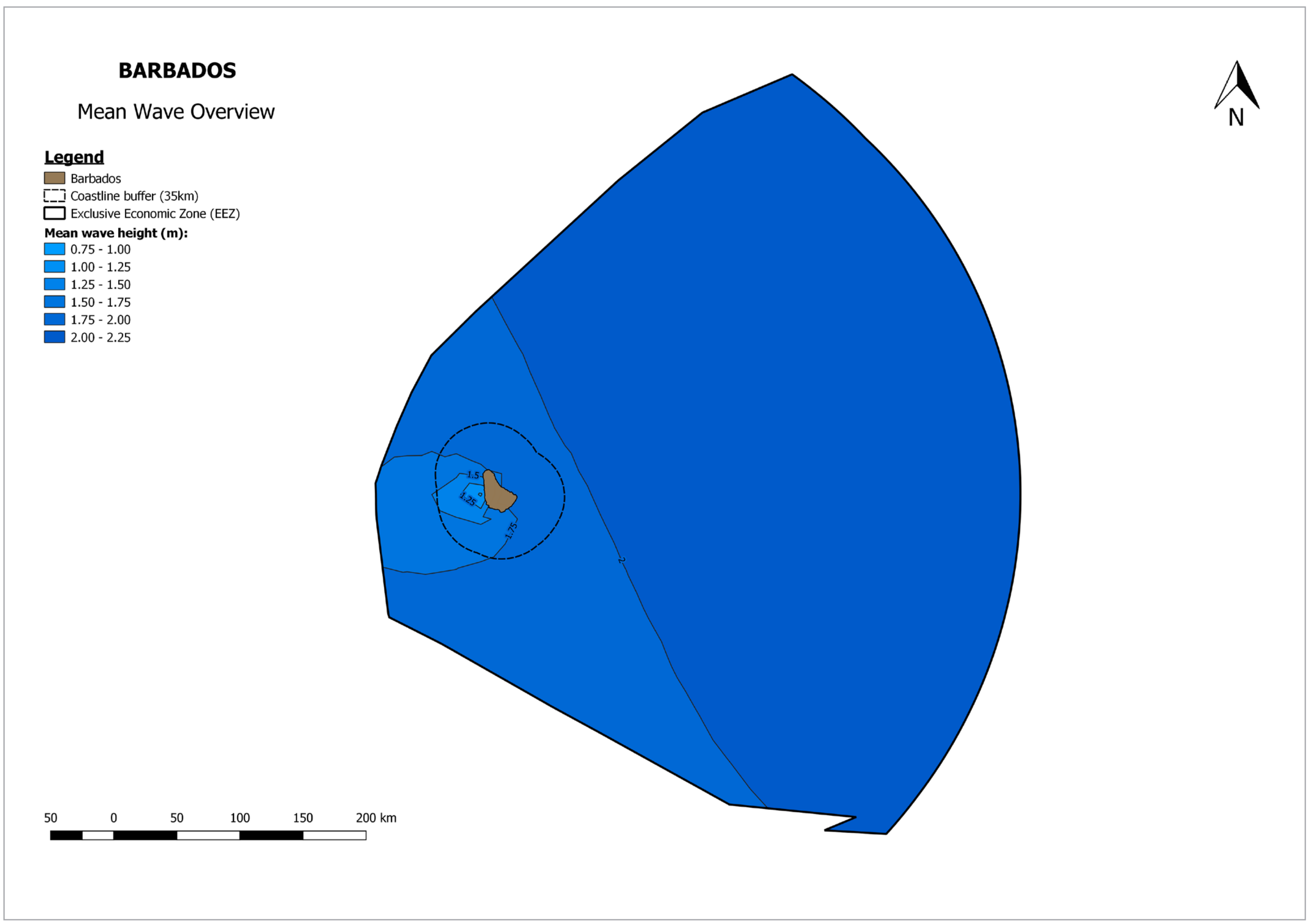
Systems have been installed in high-energy environments such as the EMEC wave test site in Orkney, Scotland which sees waves of 15m with reasonable regularity. However developers tend to prefer sites with a regular wave regime with an absence or low incidence of extreme conditions.

6.3.2 Resource in Barbados

The east coast of Barbados is exposed to the long fetch of the Atlantic Ocean and the prevailing south-easterly swell and wind wave direction. Freely available wave energy data for the region is not of sufficient resolution to undertake a detailed assessment of the available resource.

Figure 6.23 and Figure 6.24 below present the results of a broad assessment of long-term wave and wind climate undertaken by RPS (2019) using data taken from NOAA's Wavewatch III Gulf of Mexico model for the period from February 2005 to June 2019 with respect to the EEZ of Barbados. It should be noted that, while this assessment is appropriate and useful as an initial starting point to understand the wave climate of Barbados, the spatial resolution is low, and coastal and near-shore geography are not fully taken into consideration by the model. Therefore, a more detailed assessment, utilising data gathered at a local level, is strongly recommended prior to further consideration of any specific sites or areas identified.

Figure 6.23 Resource potential: Mean wave height in Barbados



As can be seen above, the mean wave height (a standard metric in wave climate assessment) on the east coast of Barbados is calculated to be within a range of 1.75m – 2m. The resource to the east of the island is shown to be relatively homogenous. The mean wave height on the west coast drops to below 1.5m which is due to the 'shadowing' effect of the land mass of the island of Barbados from the prevailing wind and swell direction to the south east.

Figure 6.24 Resource potential: Maximum wave height in Barbados

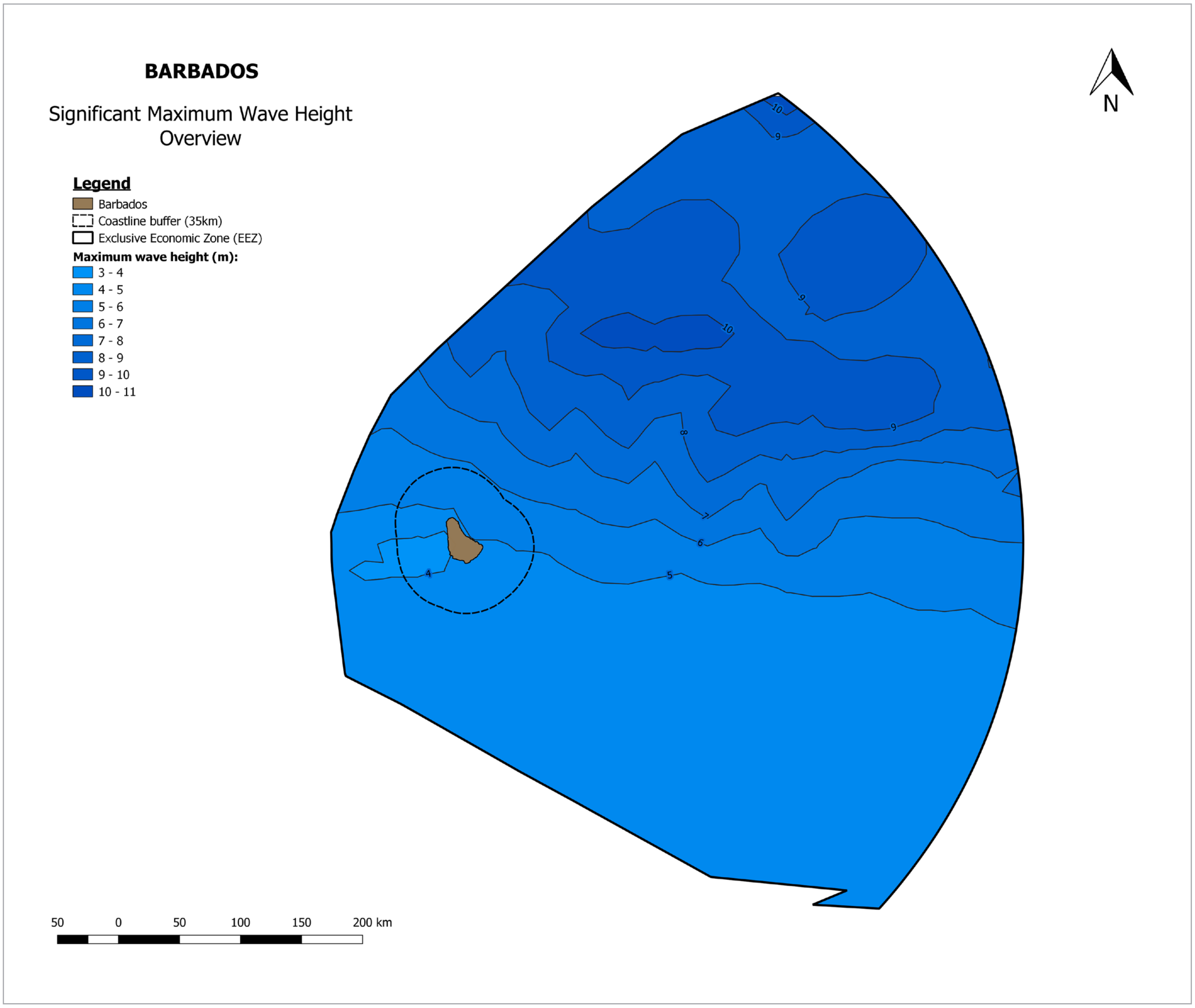
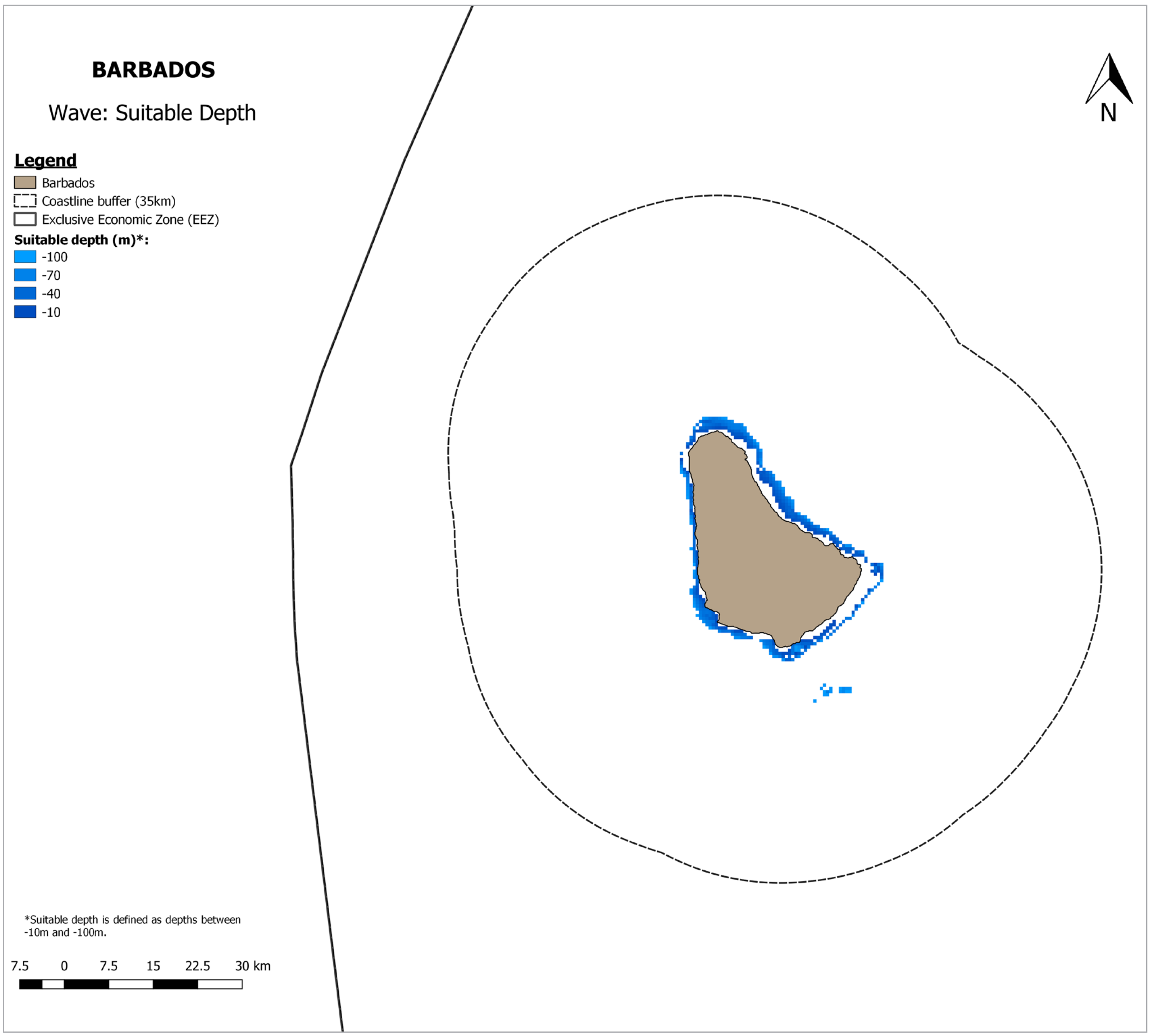


Figure 6.24 shows maximum significant wave heights recorded over a fourteen year period in the Barbados EEZ. 'Significant wave height' is a commonly used technical term referring to the average of the highest third of all waves recorded over a specific timeframe – as such the largest waves observed will be above the significant wave height.

The largest waves were observed in the northern area of the EEZ with maximum significant wave heights of between 10m – 11m in some areas. This is in marked contrast to the south of the EEZ where maximum significant wave heights were in the range of 5m. The variation in wave heights observed can almost certainly be attributed to hurricanes or tropical storms tracking towards the northern and western Caribbean. Again, the shadowing effect of the island land mass can be seen with the lowest results observed immediately off the west coast of Barbados.

In terms of suitable depths for deployment of wave energy conversion devices; Figure 6.25 shows a band of suitable depth surrounding the island. A number of the areas identified are in extremely close proximity to land, which, depending on the technology deployed, may or may not be an issue.

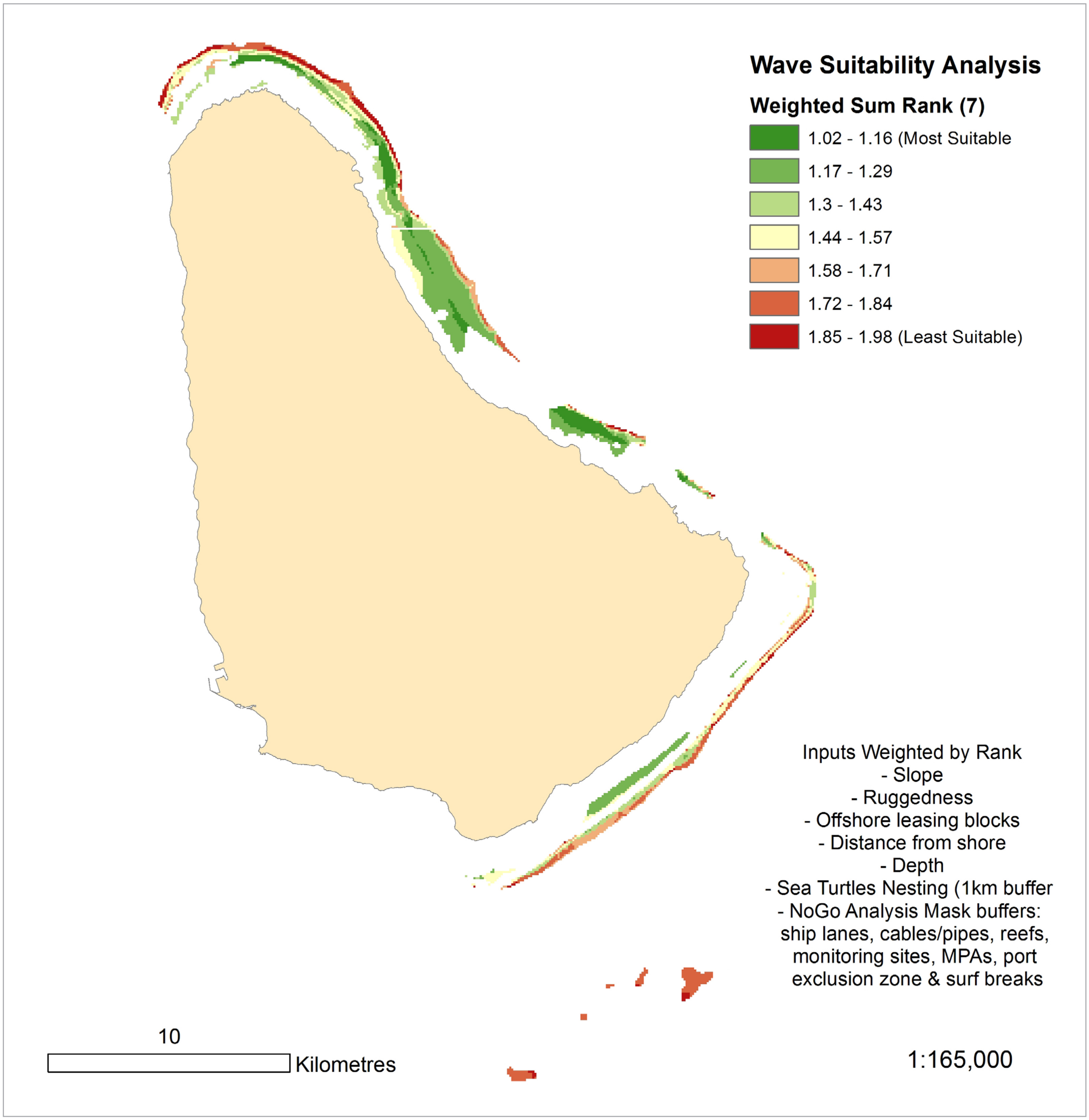
Figure 6.25 Barbados: areas with suitable sea depth for Wave Energy



6.4 / WAVE – LOCATIONAL GUIDANCE

Figure 6.26 below presents the results of detailed locational guidance analysis with respect to wave energy undertaken with use of GIS software.

***Figure 6.26** Wave - Weighted sum suitability analysis map*



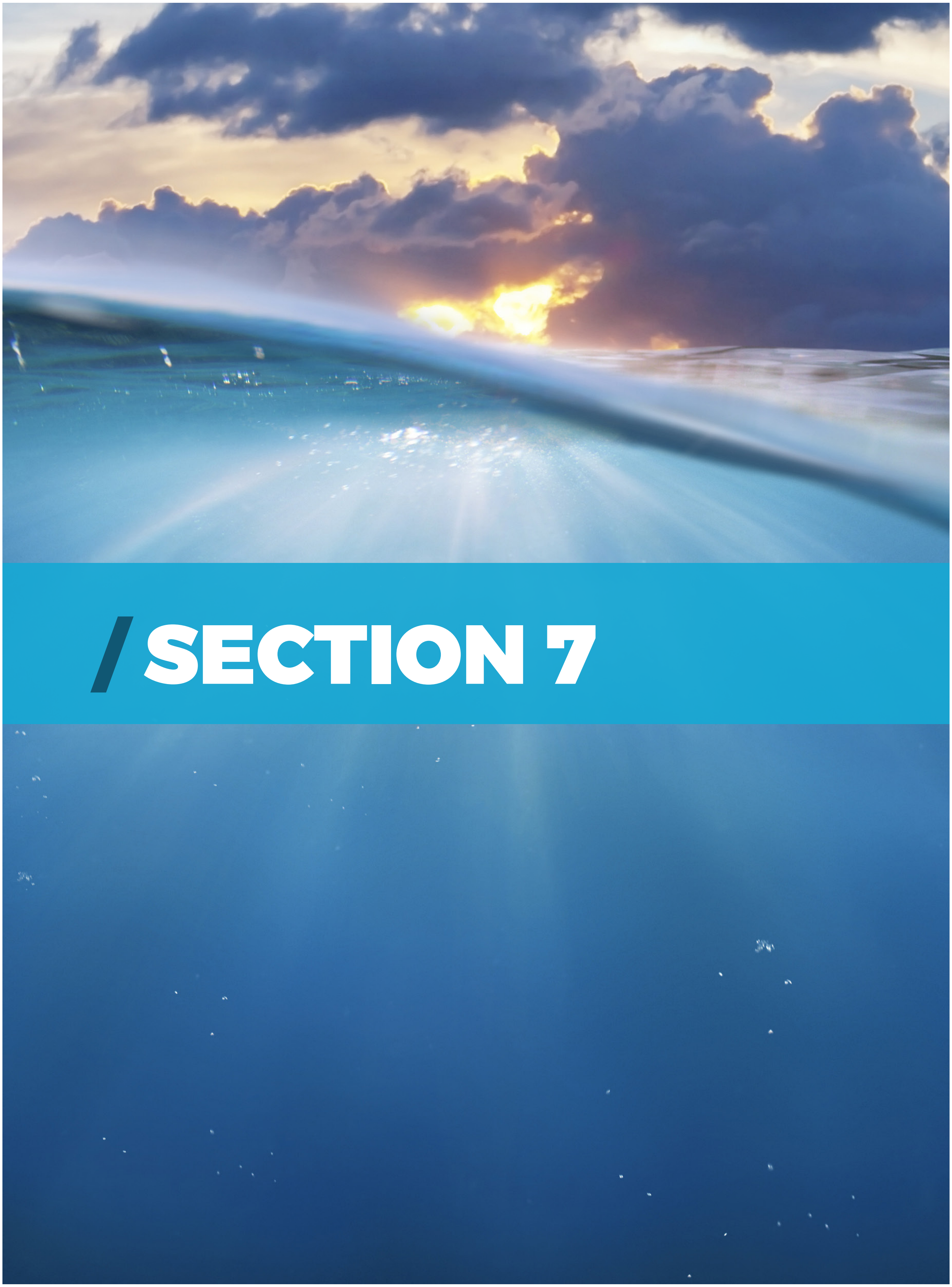
As can be seen above, a number of areas have been identified as potentially being suitable for the deployment of wave energy conversion devices within a short distance from shore. It is notable that many of the areas in the suitable band of depth have been excluded – this is due to factors such as presence of and proximity to coral reefs, turtle nesting areas, and other maritime obstacles such as pipelines and telecommunications cables. The remaining areas identified are located off of the north, east and south east coasts with the areas off the east coast being largest and scoring highest in the analysis. Each of these areas would be of sufficient size for deployment of a number of devices of varying sizes and designs.

6.5 / WAVE - DISCUSSION

Wave projects exhibit some potential in Barbados, particularly due to the consistency of the resource, but would present some significant challenges in terms of technology readiness. The best deployment locations are seen to be located on the east, north, and south eastern coasts of the island which are open to the full fetch of the Atlantic Ocean.

The consistency of the wave regime, driven by trade winds which are present for much of the year, although seen as a positive could also create some operational difficulties as calm periods are generally required for installation and maintenance operations. Wave technologies are generally designed for waters of less than 100m depth. Coastal bathymetry and potential anchoring and mooring challenges at any intended deployment site would need to be investigated thoroughly.

Whilst a large scale commercial application of wave energy technology is not feasible at present as the technology has not been sufficiently proven at demonstrator scale, there could be a significant opportunity for Barbados to take the lead in demonstrating wave energy technology. Efforts could range from potentially facilitating testing and research centred on individual wave energy devices at varying scales to attraction and hosting of larger pre-commercial devices or commercial demonstrator arrays at full scale. Combination of wave energy technology in any new build breakwater projects may also be worthy of consideration as a less technologically risky option. An additional option may be to encourage 'co-location' of floating OSW, and potential future wave energy pilot demonstration and eventual wave energy commercial projects.



/ SECTION 7

/ TIDAL STREAM/OCEAN CURRENT ENERGY CONVERSION

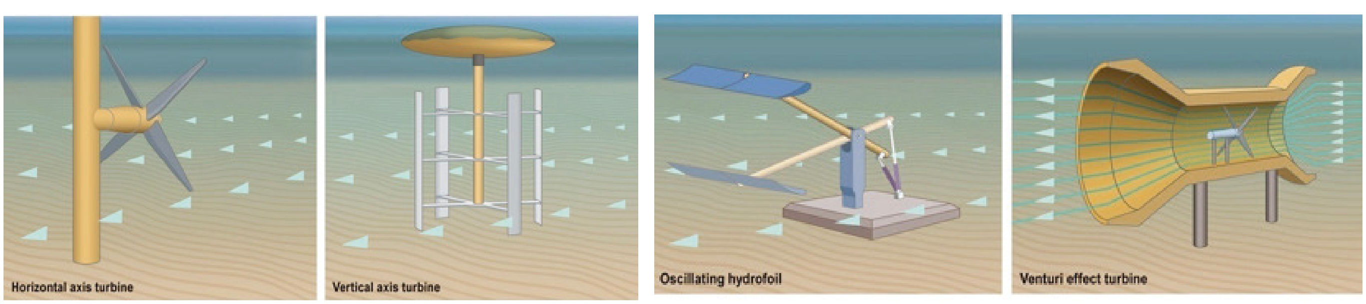
7.1 / TIDAL STREAM/OCEAN CURRENT - OPERATING PRINCIPLE

Ocean current energy involves conversion of flowing water into mechanical movement which drives an electrical generator. Flows of water in the ocean can be mono-directional and highly consistent, such as those present in the Gulf Stream, and are a natural phenomenon caused by the interaction of numerous forces such as wind, waves, salinity, bathymetry and the rotation of the planet (Coriolis Effect). These ocean currents, which differ from tidal and wind driven surface currents, are almost always located at significant depth below the ocean surface. These flows can occur globally in numerous locations, but generally follow continental coastlines, and form large inter-continental cycles.

Tidal energy differs from ocean current energy in that flows of water are created by the rise and fall of the tides caused by the gravitational pull of the sun and moon. These flows are generally bi-directional, changing direction four times every day, and are entirely predictable. Tidal flows are often fastest between nearby islands or around peninsulas where the natural features concentrate the movement of water.

There are many concepts under development for converting ocean and tidal currents into electrical energy, some of which are outlined in Figure 7.27. These can broadly be considered to be analogous to wind turbine designs except that instead of converting the flow of air (wind) into energy, these devices are converting the flow of water into energy. Due to the nature of the resource, deployment of ocean current and tidal energy devices is highly site specific.

***Figure 7.27** Examples of ocean current, tidal flow and river flow device types*



Source: US DOE (2015)

7.2 / TIDAL STREAM/OCEAN CURRENT - DEVELOPMENT STATUS

The ocean current energy sector is at a nascent stage of development. To date there is thought to have only been one ocean current energy converter installed in full ocean conditions.

- **Japan** – IHI, Mitsui, Toshiba and the University of Tokyo have formed a long-term consortium for the development of an ocean current turbine to be deployed in the Kuroshio Current off the coast of Japan. It is understood that a 100kW device has been tested in 100m of water since 2017, and is planned to be further tested until 2020.

The tidal energy sector, although still in the early stages of pre-commercial development, is at a relatively advanced stage of development compared with other emerging ocean energy technologies. A large number of developers are actively developing tidal technologies. The number of companies on the EMEC tidal energy technology developer register currently stands at 95 (EMEC, 2019).

The tidal sector does exhibit some parallels with the wind energy industry and, as in wind, the sector has converged on the use of horizontal axis turbine technology. A number of companies are testing individual full-scale prototypes but the industry has now advanced to the stage where the first array projects have been deployed and are operational providing electrical power into the grid.

The number of active projects is too great to list in detail but selected 'flagship' projects include:

- **United Kingdom** – EMEC in Orkney has hosted around 15 tidal energy devices at various scales at its Falls of Warness tidal test facility since 2006.
- **United Kingdom** – Meygen, in the north of Scotland, is the world's first large-scale array project with 6MW currently installed, and consent for a total potential capacity of 398MW. The project, consisting of three 1.5MW Andritz turbines and one Atlantis turbine, has been operational since 2016.
- **United Kingdom** – Nova Innovation installed, commissioned and grid connected an array of three 100kW subsea turbines in Shetland, Scotland in 2016. The project is still operational.
- **United Kingdom** – Orbital Marine (formerly Scotrenewables Tidal Power) has tested a 2MW iteration of its technology at EMEC. Construction is underway for a second generation 2MW machine to also be installed at EMEC.
- **Canada** – A small number of developers including Open Hydro, Big Moon Power and Sustainable Marine Energy have installed and tested large scale devices at the Fundy Ocean Centre for Energy (FORCE), and elsewhere in the province of Nova Scotia.
- **South-East Asia** – A small number of individual devices have been installed in Singapore and Indonesia. An early stage project pipeline exists in Indonesia and the Philippines, aiming to build on initial success in demonstrating the technology in the region.

7.3 / TIDAL STREAM/OCEAN CURRENT – OPERATIONAL REQUIREMENTS AND RESOURCE IN BARBADOS

7.3.1 Operational requirements

There is limited information related to operational requirements for tidal and in particular ocean current projects. For most tidal projects there is general industry consensus that flow speeds of at least 2.5 meters per second or greater are required for commercial viability. There are; however, some industry players (notably Minesto utilising 'kite' technology) which look to utilise flow speeds of less than 2.5 meters per second.

In terms of distance to shore, fast tidal streams are generally only found close to shore where geographic features naturally speed up the flow of water, hence such projects are almost always sited within about 3km of shore or less. Ocean currents also tend to follow coastlines, but may be situated much further of shore. The flow rate of ocean current tends to be low so accessing low resource far offshore is unlikely to be commercially viable and developers would probably search for suitable sites as close to shore as possible.

In terms of depth, most tidal projects are installed in waters of around 30m to 60m. Water close to the surface will generally move fastest in tidal streams (due to seabed friction effects) and turbines need enough depth of water to allow space for the rotor diameter (about 18m for a 1MW machine), and to avoid the wave turbulence at the surface and slow-moving water at the seabed. Ocean currents are likely to be in deeper water and the main flow may not be at the surface, making site and depth selection more complex.

7.3.2 Resource in Barbados

No high-quality data on tidal or ocean current speeds has been found for Barbados. It is therefore not possible to determine the suitability of the resource with certainty. However, it is apparent that due to its open coastal geography it is extremely unlikely that suitable sites of any scale exist for tidal projects. For ocean currents it is understood that flow rates are around 0.5 meters per second maximum, which is too low for a viable project given the current state of technological development. The appearance of new or better data or local knowledge may challenge these assumptions.

7.4 / TIDAL STREAM/OCEAN CURRENT – LOCATIONAL GUIDANCE

Recognising the limited potential and lack of resource data regarding this technology, no weighted sum suitability analysis was undertaken for tidal energy in Barbados. It is considered highly unlikely that any suitable locations exist for these technologies.

7.5 / TIDAL STREAM/OCEAN CURRENT - DISCUSSION

Ocean current energy, whilst sharing synergies with tidal energy, is at a very early stage of development with no active demonstrations in real sea conditions beyond the Japanese project listed above. It therefore represents a very high technology risk. Suitability of resource is also uncertain. As indicated above it is considered that Ocean Current Energy has low potential in Barbados in the near to medium term.

Tidal technology, whilst deployed in arrays in the UK, is considered likely to be unsuitable for Barbados due to the apparent lack of sufficient current velocities near to the coast. This is as a result of the natural coastal geography of Barbados and, although not backed up by data, this can be considered a firm assumption based on professional judgement and extensive experience in site identification for tidal energy projects. Unless unexpected data regarding current speed is forthcoming it is considered that tidal technology is unsuitable for deployment in Barbados.

SECTION 8

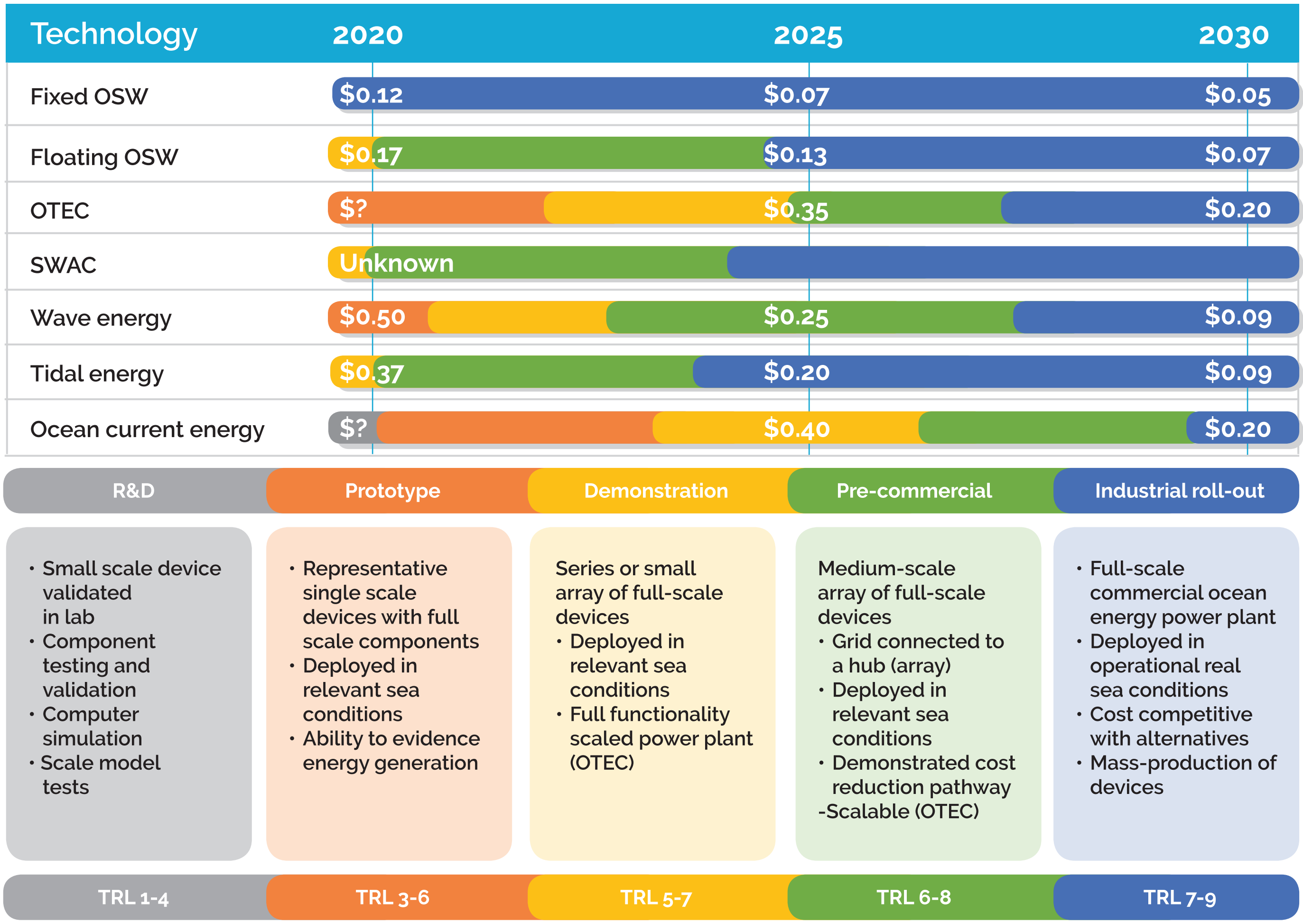
/ OVERVIEW AND RECOMMENDATIONS

8.1 / OVERVIEW OF CURRENT DEVELOPMENT STATUS OF SELECTED TECHNOLOGIES

The development status of each of the selected technologies discussed in this report are summarised in Figure 8.28 along with a 'best informed estimate' of projected development pathway and LCOE now and in the future. The commonly used Technology Readiness Level (TRL) benchmarking scale is used in this assessment and an overview of the meaning of wide TRL brackets is also provided in Figure 8.28. The projected development pathway is intended to reflect general 'global' technical readiness and commercial availability, however local market or environmental conditions may improve or adversely impact upon this timeline.

For OSW and tidal energy LCOE values are backed up by industry studies. For other technologies, due to a lower level of technical and commercial maturity, there is a paucity of cost information available and so figures given are estimates and are unavoidably subject to a significant margin of error. For some cases no cost figures are given where no reliable cost information is available from the industry.

Figure 8.28 Summary of the technology readiness and likely development timescales of the selected technologies for global application with LCOE estimates



Source: Adapted from Ocean Energy Forum (2016).

8.2 / OVERVIEW OF POTENTIAL IN BARBADOS

Barbados is faced with high electricity prices with a high carbon footprint from electricity generation, and it is sensible that it should be exploring how the technologies considered in this report could be utilised in addressing these issues. The Government of Barbados has also outlined in its National Energy Policy 2019-2030 its objective to decarbonise and move to utilise 100% renewable sources of energy by 2030 - which again is sensible and consistent with exploring all available renewable energy technology options.

This report has shown that, in terms of resource potential and availability of suitable sea depths in proximity to land, Barbados has good potential for floating OSW, wave energy, OTEC and SWAC, with potential for fixed OSW likely to be highly restricted. Each technology is however at different stages of technological readiness and offer different value propositions. Further work is required to identify promising areas for development to take account of the level of electrical demand, grid capacity, other sea users and other technical parameters. Tidal and ocean current technology is identified as having very low potential for deployment.

For floating OSW (and fixed OSW if a viable location can be identified) achieving a scale of project substantial enough to deliver reasonable economies of scale will be a major consideration. It may be beneficial to contemplate a regional approach, through collaboration with neighbouring islands, to try and tackle this and ensure sufficient activity in the region to generate competition from manufacturers and the supply chain.

For OTEC, in contrast to OSW, economies of scale are unlikely to be a problem with proposed projects generally under 10MW. Technological risk and economic considerations (i.e. achieving an acceptable LCOE) are however much more uncertain and pose the main barriers to delivering a project in Barbados. Tapping into additional revenue streams by coupling with SWAC projects for example may provide a route to delivering additional value, but this is not straightforward and development timescales have proven to be very lengthy. Standalone SWAC projects also look promising, noting the highly site specific nature of these projects necessitating detailed assessment of opportunities.

It is also worth noting that the low carbon agenda drives further electrification of industry and transport (including shipping). It can therefore be expected that demand will increase for green electricity. In that sense, there may be an opportunity to use MRE technologies to reduce the carbon footprint of industry, for example. Other future markets being explored for OSW globally include production of green hydrogen by connecting wind turbines to electrolysers. A recently announced project in Germany is looking to further combine OSW powered green H_2 with captured CO_2 to create carbon neutral aviation fuel (Recharge, 2019). Other projects, such as HySeas III in Scotland, is looking to use green hydrogen to power shipping (HySeas III, 2019). In the medium to long term there could be an opportunity for Barbados to use green ocean energy to power new industries, such as a hydrogen bunkering and refuelling for low carbon cruise liners, the incentive being to unlock an indigenous clean energy resource with potential that far exceeds the current projected electricity demand, and can play a pivotal role in moving away from the fossil fuel-based system on which Barbados depends at present, while helping to achieve the climate ambitions set out by the Government.

8.3 / CONCLUDING REMARKS

In addition to presenting a technology review of numerous relevant ocean energy technologies, this report has analysed available data on marine energy resource and other datasets to allow evidence-based discussion and recommendations to be made on the suitability of each technology for consideration for near term deployment. Results of Locational Guidance work for fixed OSW, floating OSW, OTEC, and wave energy have also been presented and discussed.

This report therefore provides a solid foundation on which to base future work to identify and assess locations of particular potential for future projects. This is now being taken forward during 2020 through the suite of technical, financial and other studies to be carried out via the PSSEP project Ocean Energy Studies Component.

The work carried out and methodology applied in this report is replicable elsewhere in the Caribbean region and in other SIDS and can deliver similar benefits. These benefits can be summarised as;

- 'Screening' of viable technology types and narrowing of technology options - thus lending focus to future discussion and policy development.
- A much-improved understanding of potential siting of future offshore arrays, taking into account resource availability and other key considerations.
- Understanding of possible additional benefits outside of MRE including contribution to the wider Blue Economy agenda.

Overall, this report has delivered improved understanding of the extensive potential for ocean energy deployment in Barbados across numerous technologies in terms of matching resource potential with technical and commercial readiness. This is consistent with and will support the stated ambition of the Government of Barbados in its National Energy Policy to fully decarbonise by 2030.

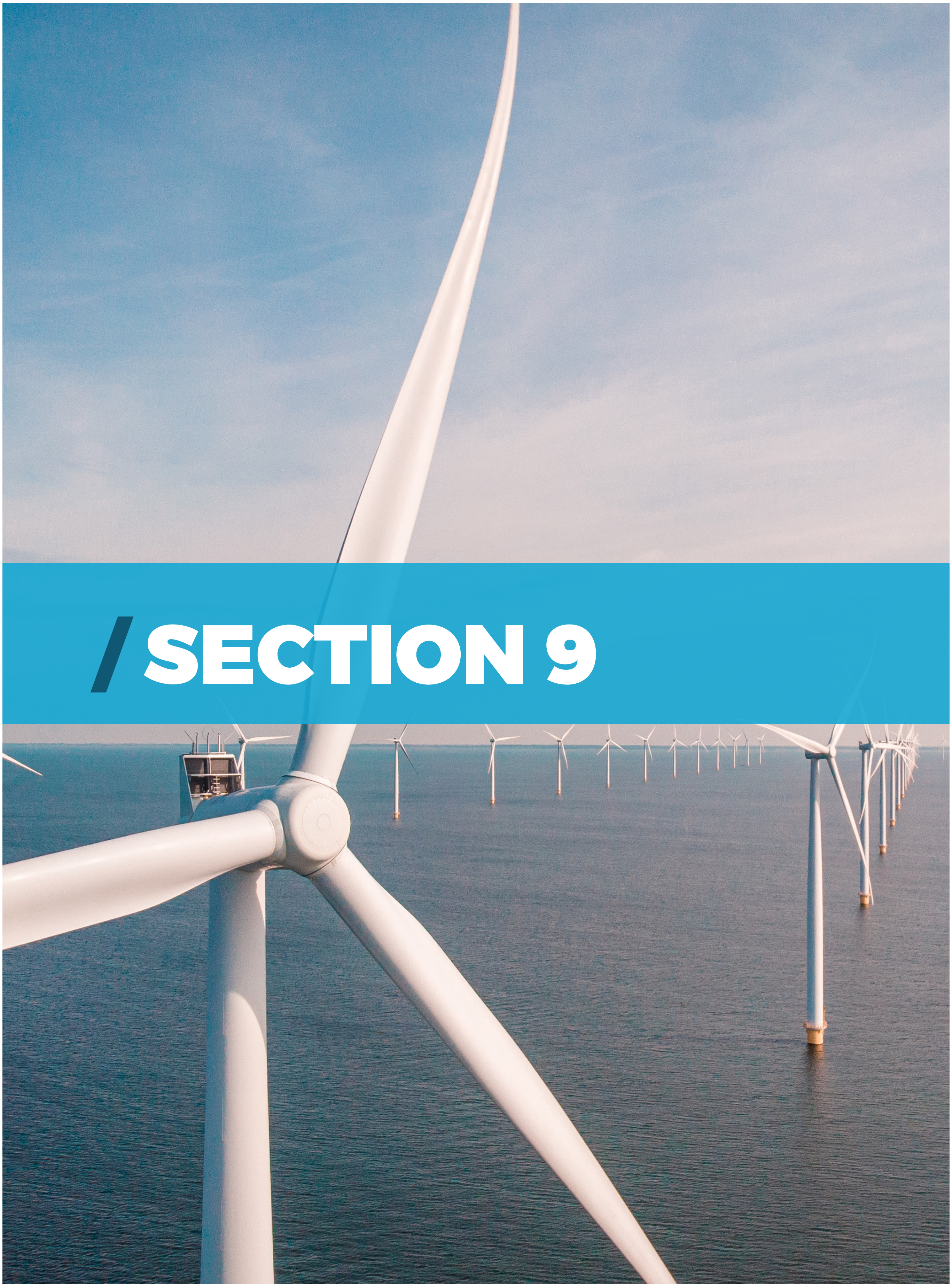
8.4 / LINKS TO FURTHER INFORMATION

In production of this report every attempt has been made to fairly and accurately describe and evaluate the current status of the various technology sectors within the Ocean Energy industry. However, due to the breadth of activity underway and in the interest of brevity, it has been necessary to be selective in the information presented. Numerous industry specific reports are available which supplement the information in this report and which the reader should consult for further detail. To this end links are provided to a range of recent reports in Table 8.2.

Table 8.2 Reports of relevance to the selected marine energy technologies

Report title	Year	Source
CAF: Pre-feasibility Study for Deep Seawater Air Conditioning Systems in the Caribbean	2015	https://www.esmap.org/sites/esmap.org/files/Caribbean_SWAC_Final_Report_01-10_web.pdf
International Energy Agency: Offshore Wind Outlook 2019 (Special Report)	2019	https://webstore.iea.org/offshore-wind-outlook-2019-world-energy-outlook-special-report
International Renewable Energy Agency (IRENA). Ocean Energy 'Technology Briefing' reports	Various	https://www.irena.org/publications/Our-Collections#renewable_readiness_assesments
IRENA: A Path to Prosperity - Renewable Energy for Islands	2016	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Path_to_Prosperity_Islands_2016.pdf
IRENA: Hydrogen – A renewable energy perspective	2019	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf
IRENA: Future of Wind – deployment, investment, grid integration and socio-economic aspects	2019	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf
Ocean Energy Europe: Ocean Energy key trends and statistics 2018	2019	https://www.oceanenergy-europe.eu/wp-content/uploads/2019/04/Ocean-Energy-Europe-Key-trends-and-statistics-2018_web.pdf
Ocean Energy Strategic Roadmap: Building Ocean Energy for Europe	2016	https://webgate.ec.europa.eu/maritimeforum/sites/maritimeforum/files/OceanEnergyForum_Roadmap_Online_Version_08Nov2016.pdf
Ocean Energy Systems: Vision for international deployment of ocean energy	2017	https://www.ocean-energy-systems.org/publications/oes-vision-strategy/document/oes-vision-for-international-deployment-of-ocean-energy-2017-/
US Department of Energy: 2018 Offshore Wind Market Report.	2019	https://www.energy.gov/eere/wind/downloads/2018-offshore-wind-market-report
Wind Europe: Offshore Wind in Europe, key trends and statistics 2019.	2020	https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf
World Bank Group: Going global – expanding offshore wind in emerging markets.	2019	http://documents.worldbank.org/curated/en/716891572457609829/pdf/Going-Global-Expanding-Offshore-Wind-To-Emerging-Markets.pdf

SECTION 9



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SECTION 10

APPENDIX A / THEORETICAL RESOURCE POTENTIAL OUTLINE METHODOLOGY

INTRODUCTION AND AIM

The aim of this appendix is to provide a brief overview of the methodology used and results obtained in undertaking analysis to calculate headline figures for the Theoretical Resource Potential for selected technologies in Barbados.

The Theoretical Resource as defined in this report considers the area of sea with suitable depth and within suitable distance from shore (set depending on the technology but up to a maximum of 50km as informed by background research and consultation with industry) and calculates the number of megawatts that could be installed in the area identified.

METHODOLOGY

A three step process was used to calculate Theoretical Resource potential;

- STEP 1 – Identify and quantify scope and broad area of interest
- STEP 2 – Map appropriate distance from shore and suitable sea depth
- STEP 3 – Calculate Theoretical Resource potential

Each step is discussed in turn below.

STEP 1 – Identify and quantify scope and broad area of interest

The Exclusive Economic Zone (EEZ) for Barbados was plotted as the starting point for analysis. Technologies were selected for inclusion in the analysis as Fixed OSW, Floating OSW (split into conventional and deep), and OTEC. SWAC, wave, and tidal/ocean current were excluded sue to lack on information on which to base analysis. Additionally the population (~292,000), peak electrical demand (~155MW), and average electrical demand (~104MW) of Barbados were quantified as points for reference in later stages of the analysis.

STEP 2 – Map appropriate distance from shore and suitable sea depth

Appropriate distances from shore were selected for each technology. For all OSW technologies this was set at 3-50km from shore and for OTEC at 0-30km from shore.

The available sea area for installation of each technology was mapped based on appropriate distance from shore and the key parameter of suitable sea depth. Suitable sea depths were determined as per Table 10.3.

Table 10.3 Suitable sea depths for installation of each technology

Technology	Suitable sea depths
Fixed OSW	10-60m
Floating OSW (conventional)	60-200m
Floating OSW (deep)	200-1000m
OTEC	750-1250m

STEP 3 – Calculate Theoretical Resource potential

An estimate was made for the number of MW's of generation that could be installed in the available sea area identified considering typical device size and spacing. The figures used for this are outlined in Table 10.4. The output of this analysis gives a figure for the Theoretical Resource Potential.

Table 10.4 Assumed capacity of each installation and spacing

Technology	Suitable sea depths	Suitable sea depths
Fixed OSW	7	1.54km
Floating OSW (conventional)	7	1.54km
Floating OSW (deep)	7	1.54km
OTEC	10	10km

Note that whilst the assumptions for OSW are robust and determined by analysis of industry data, the figures for OTEC are not. There are few operational examples of this technology at scale and no information on sensible spacing. It is however unlikely that two plants could be placed in close proximity to each other due to the potential interaction between water intakes and outputs, so, in the absence of data, a conservative estimate of required spacing was made. In practical terms, if looking to scale up from 10MW to 20MW for example, it is recognised that it would be likely that this would be done by expanding an existing plant rather than by building another in proximity. Nonetheless, the assumptions used are useful in providing relative resource potential for any one area over another.

RESULTS

The outcome of STEP 3 is to identify the theoretical resource potential for each technology for Barbados. This is presented in Table 10.5.

Table 10.5 Theoretical Resource for each technology

Technology	Maximum Theoretical Resource Potential (MW)
Fixed OSW	0 (unless within 3km from shore)
Floating OSW (conventional)	189
Floating OSW (deep)	8,344
OTEC	160
Total	**8,693**

The analysis shows vastly more theoretical potential than demand in Barbados. Whilst the figures do not allow for the capacity factor of technologies installed, it does indicate that the selected MRE technologies have substantial potential to contribute to the energy mix.

Analysis of theoretical potential should always be read carefully as there are numerous factors which affect the technically exploitable resource which are not considered in such calculations. For instance there are numerous and various constraints and other sea uses which might exclude development from areas of sea.

APPENDIX B / WEIGHTED SUM SUITABILITY ANALYSIS OUTLINE METHODOLOGY

INTRODUCTION AND AIM

Spatial analysis and production of 'Locational Guidance' maps to assist the potential development of offshore energy installations in waters surrounding Barbados was commissioned in 2017 under the Marine Energy Component (Component 2.2) of the Public Smart Energy Program (PSSEP) in Barbados. This work involved compiling various sources of data into GIS map format, then undertaking scoring and weighting of maps to identify areas of potential suitability for the following technologies;

- Fixed OSW
- Floating OSW
- OTEC (offshore floating)
- Wave

Selected outputs are presented in this report under 'Locational Guidance' subsections. The aim of this work was to aid in early identification of the most promising sites to take forward for further consideration in future. The work undertaken is fully presented in Baldwin (2018) and this appendix provides a very brief and simplified overview of the methodology undertaken for this analysis.

METHODOLOGY

A four step methodology was undertaken;

- STEP 1 – Data collection and conversion
- STEP 2 – Determination of suitability criteria for each technology
- STEP 3 – Creation and preparation of layers to be utilised in the weighted sum calculations
- STEP 4 – Weighted sum calculation

Each of the steps is discussed in turn below before consideration is also given to the limitations of the assessment.

STEP 1 – Data collection and conversion

An extensive exercise was undertaken to identify, gather, and assess existing biological, ecological, space-use, jurisdictional and biophysical spatial data for the coastal marine waters of Barbados. Relevant data was standardised into a common global geographic coordinate system.

STEP 2 – Determination of suitability criteria for each technology

Selection was made of the appropriate data sets to consider for each technology. Data was identified as either being suitable for use as a weighted layer or exclusion layer.

STEP 3 - Creation and preparation of layers to be utilised in the weighted sum calculations

The data for each layer was processed into an appropriate format for use in the analysis. This involved specifying ranges for each data layer for each technology and undertaking suitability scoring for these selected ranges. Exclusion areas were amalgamated and removed from analysis.

STEP 4 – Weighted Sum Calculation

The weighted sum was calculated by applying a relative importance score to each layer produced in Step 3, then by multiplying each of the layers created with the corresponding weighting, and then adding the resulting layers together. The 'Locational Guidance' maps in the body of this report are the outputs of this analysis.

RESULTS

The analysis outlined above resulted in the production of suitability weighted sum maps as presented in the main body of this report. In each map, areas with the highest suitability scoring are coloured bright green and areas with the lowest are coloured red. All intermediate scores are the graded appropriately between these two points. Areas coloured red are therefore not deemed unsuitable for development, rather they are considered to be likely to be less preferred. It should be noted that analysis of the outputs produced is limited by the quality and extent of data available, although it is considered fit for purpose.